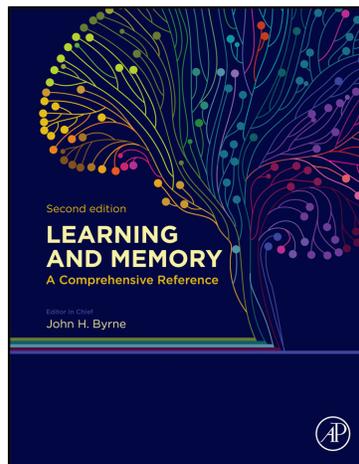


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## 2.26 Spacing Effects on Learning and Memory<sup>☆</sup>

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<b>2.26.1</b>	<b>Introduction and Overview</b>	465
<b>2.26.2</b>	<b>Theories of the Spacing Effect</b>	466
2.26.2.1	Deficient Processing	466
2.26.2.2	Encoding Variability	467
2.26.2.3	Study-Phase Retrieval	468
2.26.2.4	Multiprocess Accounts	468
2.26.2.5	Consolidation	469
<b>2.26.3</b>	<b>Schedules of Spacing for More Than Two Presentations</b>	469
<b>2.26.4</b>	<b>Optimal Spacing Gaps</b>	470
<b>2.26.5</b>	<b>Spacing and Inductive Learning</b>	471
<b>2.26.6</b>	<b>Spacing and Metacognition</b>	472
<b>2.26.7</b>	<b>Spacing Effects in Authentic Educational Settings</b>	474
2.26.7.1	Studies of the Spacing Effect in Classrooms	474
2.26.7.2	Studies of the Spacing Effect in Medical Education	477
2.26.7.3	Other Approaches to Using Spacing: Successive Relearning and Cumulative Exams	478
2.26.7.4	Intensive Foreign Language Courses – A Reverse Spacing Effect?	479
<b>2.26.8</b>	<b>Summary and Conclusion</b>	480
<b>Acknowledgment</b>		481
<b>References</b>		481

### 2.26.1 Introduction and Overview

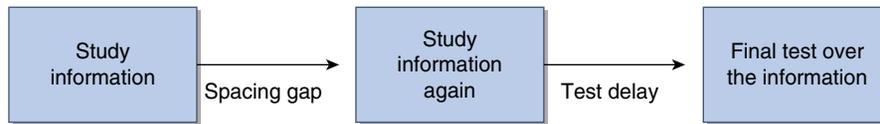
Repetition is fundamental to learning. Whether the goal is to achieve that perfect golf swing, to speak a foreign language, or to run a marathon, practicing something over and over again is essential for developing the knowledge and skills that are needed to achieve mastery. It perhaps goes without saying that anyone seeking to learn a new concept or skill would hope to retain it over a meaningful period of time and apply it in different situations. A question of great practical relevance, therefore, is how to engage in repeated practice in a way that facilitates long-term durability and flexibility of the information learned.

A long tradition of research has shown that the power of repetitions to enhance knowledge and skills greatly depends on how those repetitions are scheduled. In what has become a classic study in learning and memorization, [Ebbinghaus \(1885/1913\)](#), using his own memory for nonsense syllables, was the first to demonstrate that repeated efforts to memorize information at different points in time produced better learning of the information, and increased its resistance to forgetting, compared to memorizing the same amount of information within a single session. Over 130 years of research since this landmark study has confirmed that practice repetitions that are distributed—i.e., spaced out in time—enhance learning in a variety of domains. The “spacing effect” has been one of the most reliable and widely studied phenomena in memory research, with a literature so vast that several review articles have been produced just in the last several years alone (e.g., [Carpenter et al., 2012](#); [Carpenter, 2014](#); [Cepeda et al., 2006](#); [Delaney et al., 2010](#); [Gerber and Toppino, 2015](#); [Kuepper-Tetzel, 2014](#); [Rohrer, 2015](#); [Son and Simon, 2012](#); [Toppino and Gerber, 2014](#)).

The typical design of a spacing effect study is illustrated in [Fig. 1](#). After an initial opportunity to study some information (e.g., foreign language vocabulary words), participants have an opportunity to study it again on at least one more occasion. These two study episodes are separated by a *spacing gap*—the period of time, manipulated experimentally, that elapses in-between exposures to the information. When information is repeated immediately, the spacing gap is 0 and the exposures are considered “massed,” whereas any two exposures occurring at nonzero gaps are considered “spaced.” When performance is assessed after some, usually fixed, period of time (the *test delay*) as a function of different spacing gaps, the literature overwhelmingly shows that spaced repetitions lead to better performance than massed repetitions.

A related effect often referred to in the context of spacing is the “lag effect” – the tendency for longer spacing gaps to produce better memory retention than shorter, nonzero spacing gaps. Both spacing effects and lag effects have often been referred to under the umbrella term “distributed practice,” referring to the more general finding that longer spacing gaps tend to produce better learning than short nonzero spacing gaps or massed repetitions (e.g., [Son and Simon, 2012](#); [Toppino and Gerber, 2014](#)).

<sup>☆</sup>*Change History:* April 2016. Shana K Carpenter updated the text and references, added figures and a new section “Consolidation.” This is an update of R.L. Greene, 2.06 – Repetition and Spacing Effects, In *Learning and Memory: A Comprehensive Reference*, edited by John H. Byrne, Academic Press, Oxford, 2008, Pages 65–78.



**Figure 1** Diagram of a typical spacing effect study. After studying information once, participants study it again after a period of time referred to as the spacing gap (also referred to as the interstudy interval, or ISI). After the last study session over the information, memory is tested after a period of time referred to as the test delay (also referred to as the retention interval, or RI).

Spacing effects occur whether information is repeated at the item level, such that the same item occurs again immediately after its first presentation, versus after a few seconds or minutes have passed (Carpenter and DeLosh, 2005), and also at the session level, such that information is studied repeatedly within the same study session (e.g., within a 30-min period) versus across different study sessions (e.g., 15 min on 1 day, followed by 15 min on another day) (Bloom and Shuell, 1981). In either case, information that is spaced out in time (across items or across sessions) is better remembered later compared to information that is repeated at nonspaced intervals.

The benefits of spacing are ubiquitous and apply to a number of different memory-based outcomes, including recall and recognition (Cepeda et al., 2006), frequency judgments (Greene and Stillwell, 1995; Hintzman, 1969), and the ability to extract and apply general rules and concepts (Kornell and Bjork, 2008). The finding has been demonstrated across a variety of age ranges, from infants (Cornell, 1980) to older adults (Balota et al., 1989; Simone et al., 2013), and across a variety of learning tasks ranging from simple word lists (Melton, 1970) to more complex procedural tasks such as performing surgery (Moulton et al., 2006). The effect has been demonstrated in nonhuman species as well. In addition to strengthening conditioned responses in rats (Domjan, 1980; Lattal, 1999) and autoshaping in pigeons (Rescorla and Durlach, 1987; Terrace et al., 1975), spacing of repeated trials has been shown to increase the durability of habituation and sensitization responses in basic organisms such as *Aplysia* (Carew et al., 1972), honeybees (Deisig et al., 2007), and *Drosophila* (Tully et al., 1994).

The consistency of the spacing effect makes it a fascinating puzzle for theoretical research and a golden opportunity for applied research. Particularly in the realm of education, the potential for spaced distribution of study to enhance student achievement is ever present but has been historically underexplored (e.g., see Dempster, 1988). In recent years, however, research on the spacing effect has begun to address the applied questions of relevance to education. This chapter highlights key aspects of the literature on spacing effects that have addressed: (1) the theoretical mechanisms that have been proposed to explain the benefits of spacing, (2) optimal spacing gaps for maximizing long-term retention, (3) the benefits of spacing for enhancing learning of categories and concepts, (4) whether learners know about, and utilize, the benefits of spacing, and (5) whether spacing is effective for enhancing learning in authentic educational contexts.

## 2.26.2 Theories of the Spacing Effect

One of the most well-studied questions is *why* spacing enhances learning. A number of hypotheses have been proposed that have inspired a large number of investigations aimed at identifying the mechanism(s) responsible for these benefits. Although there is yet to be a unifying theory that explains many instances of the spacing effect across different tasks and diverse populations, the mechanisms responsible for the effect have been attributed at one time or another to one or more of the following processes.

### 2.26.2.1 Deficient Processing

One of the earliest accounts of the spacing effect was based on deficient processing. When information is encountered more than once, the processing devoted to that information tends to be strongest at first and then declines with each subsequent encounter. When repetitions occur close together in time, each occurrence after the first is associated with a higher degree of familiarity and redundancy, resulting in less attentional processing applied to repeated items than when the same repetitions are spaced over time. This view proposes, therefore, that the spacing effect is driven by deficient processing on the second and subsequent occurrences of massed items relative to spaced items.

Consistent with this view, Hintzman et al. (1973) found that the accuracy of source memory judgments declined from the first to the second occurrence of a massed item, but less so for a spaced item. Participants encoded a number of words that were presented twice—first auditorally and then visually, or vice versa—at either spaced or massed intervals. Later when asked to remember the modality in which each presentation occurred (visual or auditory), overall memory was better for the first presentation than the second. The decrement in memory for the modality of the second presentation was worse for massed items relative to spaced items, however, indicating that the second occurrence of a massed item is particularly poorly remembered. The idea that massed repetitions receive deficient processing has also been supported by studies that allow participants to rehearse items out loud or pace themselves through a list of items during encoding. These studies show that massed repetitions, relative to spaced repetitions, receive fewer overt rehearsals (Delaney et al., 2012; Rundus, 1971) and less overall study time (Shaughnessy et al., 1972).

Findings from the neuroimaging literature also support the idea of deficient processing. Functional magnetic resonance imaging studies have revealed that when a stimulus is repeated, the degree of neural activation in a particular brain area associated

with that stimulus is lower upon the second presentation compared to the first. This phenomenon—*repetition suppression* (Henson and Rugg, 2003)—is most pronounced when the repetitions occur close together in time. When the repetitions are spaced apart, the neural activation associated with the second occurrence of the item increases, resulting in reduced repetition suppression (Henson et al., 2000; Xue et al., 2011). Repetition suppression therefore appears to be a neural correlate of the deficient processing associated with massed items.

If spacing effects are driven by deficient processing of massed items, then the effect should be reduced or eliminated under conditions that encourage participants to process subsequent occurrences of massed items. Indeed, some research has demonstrated that the spacing effect can be attenuated under conditions that are designed to increase attention to the second occurrence of an item. For example, in exploring participants' memory for sentences that were read aloud, Dellarosa and Bourne (1985) observed the usual spacing effect for sentences that were repeatedly presented by the same speaker (either a male voice or a female voice each time), but a complete elimination of this effect when the same sentences were repeated by different speakers (first in a female voice and then in a male voice, or vice versa).

Relevant to the idea of deficient processing is *displaced rehearsal*. This idea was put forth by Hall (1992) to explain the tendency for spacing effects to be stronger in lists containing a mixture of both massed and spaced items, relative to lists containing only massed items or only spaced items (e.g., Underwood, 1970; Waugh, 1970). The displaced rehearsal hypothesis proposes that during presentation of massed items, participants' attention may be diverted away and allocated elsewhere, such as rehearsing earlier items on the list. This is less likely to occur during presentation of spaced items, because they are more likely than massed items to garner full attention on each presentation. In a "mixed" list containing both massed and spaced items, rehearsal is displaced from currently presented massed items to earlier items on the list (both massed and spaced). As a result, memory for later massed items suffers, leading to an overall spacing advantage that is stronger toward the end of the list than toward the beginning. In an "unmixed" list containing either all-massed or all-spaced items, rehearsal is displaced only to earlier massed items—but not to spaced items—resulting in a particularly strong primacy effect for massed lists than for spaced lists.

Consistent with this hypothesis, Hall observed the usual spacing effect for mixed lists; for unmixed lists, the effect was diminished, and this was largely due to early items on the list showing an advantage for massed presentation over spaced presentation (whereas later items showed the opposite).

Challenging the displaced rehearsal hypothesis, Toppino and Schneider (1999) found that massed items tended to be recalled better from earlier list positions regardless of whether they were followed by additional massed items (when displaced rehearsal should be occurring) or by spaced items (when displaced rehearsal should not be occurring). Delaney and Knowles (2005) obtained further evidence that the tendency for displaced rehearsal may depend on a learner's strategy. They found results similar to Hall's (1992) when participants used a rote rehearsal strategy (encouraging displaced rehearsal) but not when they used a more elaborate story strategy, which resulted in a spacing effect even for unmixed lists. Although some studies failed to show consistent evidence for the absence of spacing effects in unmixed lists (Kahana and Howard, 2005) even under conditions of rote rehearsal (Verkoeijen and Delaney, 2008, Experiment 1), further studies have shown that the spacing effect in unmixed lists appears to depend on the *functional* spacing between massed items on unmixed lists. Displacing rehearsal onto earlier items in an all-massed list creates a situation in which massed items are essentially spaced. That is, they are processed once during initial presentation, and again when they are rehearsed during the presentation of a different, subsequent item. The presence of a spacing effect in unmixed lists, therefore, might depend on the degree to which this functional spacing interval meets or exceeds the spacing interval present in a pure list of all-spaced items (see Delaney and Verkoeijen, 2009; Verkoeijen and Delaney, 2008, Experiments 2–3).

Thus, there is some evidence that learners "borrow" rehearsal from massed items and apply it to earlier, no-longer-presented items. The rehearsal borrowing during massed items appears to be more likely to occur under conditions in which participants use a rote rehearsal strategy rather than an elaborate story strategy. Although these studies support the idea that displaced rehearsal, and deficient processing more broadly, contributes to the spacing effect, results of other studies have suggested that these accounts alone are not sufficient to explain the full range of spacing effects. Spacing effects are observed, for example, under conditions in which voluntary rehearsal would seem unlikely, such as in incidental learning paradigms (Jensen and Freund, 1981) and under conditions of divided attention (Russo et al., 1998). Spacing effects are also readily obtained in memory for pictures, which are difficult to rehearse (Hintzman and Rogers, 1973), and in studies involving young children (Cahill and Toppino, 1993; Childers and Tomasello, 2002; Cornell, 1980; Toppino, 1991), who would seem unlikely to utilize deliberate rehearsal strategies.

### 2.26.2.2 Encoding Variability

Information can be encoded in a variety of ways. Increasing the number of different ways information is encoded is believed to benefit memory because it increases the number of ways the information can later be retrieved (Martin, 1968). When information is encoded at two different points in time—i.e., spaced rather than massed—it becomes associated with a greater number of contextual cues that can increase the variety of information associated with it and facilitate its later retrieval.

According to Glengberg's (1979) component-levels theory, these cues can include contextual elements that are automatically encoded associated with the physical environment, time, or a learner's internal state. They can also include structural elements associated with the processes being engaged by the learner (e.g., rehearsal and other strategies) and descriptive elements associated with the to-be-learned information, such as its meaning or appearance. Information that is repeated at spaced intervals (or longer spacing gaps) will include a greater variety of contextual, structural, and descriptive elements than information that is repeated at massed

intervals (or shorter spacing gaps), leading to a greater likelihood that the information will be retrieved in the future, provided that the cues available are sensitive to this contextual variation.

Support for this idea comes from studies that have manipulated various types of encoding and observed that greater encoding variability reduces or eliminates the spacing effect by selectively benefitting memory for massed items. For example, [Gartman and Johnson \(1972\)](#) presented homograph words twice (e.g., *foot*), each time in the context of one meaning (e.g., a unit of measurement), or each time in the context of a different meaning (e.g., first a unit of measurement, and then a part of the body), and observed that the spacing effect did not occur in the latter case. Similarly, [D'Agostino and DeRemer \(1973\)](#) observed the usual spacing effect in memory for action phrases when those phrases were repeated within the same sentence (e.g., "The plane hit the flag pole"), but not when the phrases were repeated in the context of two different sentences (e.g., "The plane hit the flag pole" followed by "The bear climbed the flag pole"). Similarly, [Glover and Corkill \(1987\)](#); see also [Krug et al., 1990](#)) observed stronger spacing effects on memory for paragraphs that were read twice verbatim rather than paraphrased so that they were slightly different each time. In a manipulation of the physical encoding context of repeated stimuli, [Verkoeijen et al. \(2004\)](#) found that the spacing effect was significantly reduced by varying the background color (Experiment 1) or background image (Experiment 2) during two presentations of the same stimulus.

Many other studies have manipulated same versus different context during encoding and observed its effects on the size of the spacing effect. [Toppino and Gerbier \(2014\)](#) recently reviewed 48 studies on this topic and found that massed repetitions are more likely to benefit from different-context encoding (69% of the time), and spaced repetitions are more likely to benefit from same-context encoding (40% of the time) or show no difference between same-context and different-context encoding (48% of the time). There are some exceptions, however. [Bird et al. \(1978\)](#) found that spacing effects were not eliminated by encoding conditions that required participants to use two different orienting tasks to encode the same word (first a judgment of its pleasantness, and then a judgment of whether it is active or passive), as opposed to just one orienting task to encode the same word twice. Similarly, [Dempster \(1987\)](#) found that spaced presentation led to superior learning of new vocabulary relative to massed presentation, even when the vocabulary words were presented in each of three different, contextually unique sentences.

Some studies have also found that increased variability of encoding, as a function of longer spacing gaps, does not always benefit memory. [Appleton-Knapp et al. \(2005\)](#) found that presenting a product twice in either the same advertising layout (same-context) or in two different advertising layouts (different-context) differentially affected memory for the product as a function of spacing gap. Different-context encoding was better at relatively short spacing gaps, but same-context encoding was better at longer spacing gaps, such that memory for information learned under different-context conditions exhibited an inverted U-shaped pattern as a function of spacing gap. Other studies have demonstrated a similar inverted U-shaped pattern, even for information presented in same-context conditions (e.g., [Glenberg, 1976](#); [Kuepper-Tetzl and Erdfelder, 2012](#); [Toppino and Bloom, 2002](#); [Toppino et al., 2002](#); [Verkoeijen et al., 2005](#); [Young, 1971](#)). Assuming that the variability of encoding increases with greater spacing gaps, these findings suggest that some additional mechanism, beyond encoding variability, is needed to explain the spacing effect.

### 2.26.2.3 Study-Phase Retrieval

Accounts based on study-phase retrieval propose that spacing is effective because of retrieval operations taking place during the second occurrence of an item. According to this view, the repetition of an item reminds participants of the earlier occurrence of that same item, encouraging them to retrieve the earlier presentation ([Thios and D'Agostino, 1976](#)). It has long been known that retrieving information from memory produces significant benefits on long-term retention (e.g., [Carpenter, 2012](#); [Dunlosky et al., 2013](#); [Rowland, 2014](#)), and thus the study-phase retrieval view proposes that spacing is effective because it engages the mnemonic effect of retrieval ([Benjamin and Tullis, 2010](#); [Hintzman, 2004](#)).

Retrieval is more likely to occur when repetitions are spaced than massed because in the latter, the earlier occurrence of the item can be readily accessed from immediate memory, circumventing the need for full retrieval. Many studies have shown that retrieval is more effective when it is carried out under conditions in which the to-be-retrieved information is not immediately accessible, such as when a delay is inserted between encoding the item and retrieving it ([Carpenter and DeLosh, 2005](#); [Pyc and Rawson, 2009](#); [Rawson et al., 2015](#)) or when the target information must be recalled from impoverished cues ([Carpenter, 2009](#); [Carpenter and DeLosh, 2006](#)). Consistent with the desirable difficulties framework ([Bjork et al., 2013](#)), information is best learned when it is successfully recalled under difficult conditions, such as after longer spacing gaps as opposed to shorter spacing gaps.

In support of this account, some studies have shown that spacing effects are larger when participants are directly instructed to recall the earlier occurrence of an item during the second occurrence of that item ([Thios and D'Agostino, 1976](#)) or to indicate when previously presented items repeat ([Wahlheim et al., 2014](#)). The study-phase retrieval account can also explain the inverted U-shaped function that has been found in some studies (e.g., [Appleton-Knapp et al., 2005](#)). To benefit from spacing, the current presentation of an item must effectively remind participants of the previous presentation ([Benjamin and Tullis, 2010](#)). If too much time has passed—or if the second presentation is sufficiently different from the first presentation such that the current item is not recognized as a repeat of an earlier item—then the repetition is ineffective, rendering it functionally equivalent to a once-presented item. This hypothesis proposes that longer spacing gaps are not always best and that spacing effects will be sensitive to an optimal spacing gap that encourages effortful yet successful retrieval of a previous occurrence.

### 2.26.2.4 Multiprocess Accounts

Spacing effects have also been explained as a combination of two or more of these factors. [Greene's \(1989\)](#) two-process account, for example, proposes that the spacing effect observed in free recall tasks (known to be sensitive to contextual factors) is attributable to

the relatively automatic mechanisms of contextual variability enabled by study-phase retrieval, whereas the spacing effect observed in cued memory tasks (sensitive to item memory strength) is more likely attributable to voluntary deficient processing of massed items. Consistent with this view, Greene found that spacing effects in free recall occurred regardless of whether learning was intentional or incidental. Spacing effects in cued memory tasks (e.g., recognition), however, only occurred under intentional learning conditions, suggesting that voluntary processing might be contributing (but see Toppino and Bloom, 2002 for different results when presentation rates vary).

Supporting the idea that voluntary processing underlies the spacing effect in cued memory tasks, Russo et al. (1998, Experiment 1) found that the presence of a secondary tone-counting task during encoding reduced the spacing effect in tests of recognition but not in tests of free recall. Subsequent studies have also provided support for the combined effects of study-phase retrieval and contextual variability in free recall designs, proposing specifically that the enhanced contextual variability afforded by longer spacing gaps promotes memory insofar as the contextual information associated with the earlier presentation of the item can be successfully retrieved at the time of the later presentation (Raaijmakers, 2003; Verkoeijen et al., 2004, 2005). Siegel and Kahana (2014) recently referred to this as the *retrieved context account* of spacing effects.

### 2.26.2.5 Consolidation

Consolidation refers to a set of active, time-dependent processes through which memories are stabilized and rendered more resistant to forgetting. Although early in learning memories are fragile and vulnerable to disruption, after the learning experience the neural processes involved in that experience continue to be active, resulting in a strengthening of synaptic connections that ultimately leads to system-level structural reorganization (Lechner et al., 1999). Consolidation is believed to be necessary for the establishment of long-term memories, as factors that disrupt the process before it is complete—such as neural trauma (Zola-Morgan and Squire, 1990) or interference (Wickelgren, 1966)—result in significant impairments to memories.

Although consolidation is not typically listed among theoretical explanations of the spacing effect (for exceptions, see Toppino and Gerbier, 2014; Gerbier and Toppino, 2015; Smolen et al., 2016), there is growing evidence that spacing is associated with enhanced consolidation. This idea was first put forth by Landauer (1969), who proposed that the first occurrence of an item initiated a consolidation process that must run its course for the second occurrence to be most effective for learning. If the second occurrence comes too soon, it adds little neural activity to the already-active first occurrence, resulting in minimal additional consolidation. If memory for the first occurrence has consolidated by the time the second one occurs, however, the second occurrence generates as much consolidation-inducing activity as the first, resulting in a greater overall degree of consolidation.

Evidence is accumulating that the neurobiological processes believed to be involved in consolidation occur to a greater extent during spacing than during massing. In one study involving electrical stimulation of mouse hippocampal slices, long-term potentiation (LTP)—the tendency of a postsynaptic neuron to respond more readily to presynaptic activity following repeated stimulation—was stronger when the stimulation occurred every 5 min rather than every 20 s (Scharf et al., 2002). Protein synthesis-related processes—which are known to be involved in LTP and produce enhanced learning of conditioned responses in rodents (Josselyn et al., 2001)—have been found to be relatively stronger following spaced training than massed training of behavioral memory tasks in mice (Genoux et al., 2002). Disruption of these processes—for example, through a protein synthesis inhibitor—results in a reduction of LTP that is more pronounced for LTP induced by spaced stimulations relative to massed stimulations, and also a reduction in the behavioral effect of spacing on contextual fear conditioning (Scharf et al., 2002). The growing literature on the molecular processes involved in spacing, and how these may coincide with consolidation, have recently been reviewed in detail by Smolen et al. (2016; see also Naqib et al., 2012; Philips et al., 2013).

In humans there is evidence that sleep facilitates consolidation. After learning a new task, participants who sleep overnight prior to completing a final criterial test over that task tend to perform better than participants who remain awake between learning and testing (Mazza et al., 2016; Walker and Stickgold, 2004). The tendency for memory to benefit more from spaced repetitions that occur on different days, compared to massed repetitions occurring on the same day, could be partially due to the fact that participants typically sleep in between spaced repetitions but not in between massed repetitions. In the only known study to investigate this, Bell et al. (2014) found that two study sessions spaced apart by 12 h resulted in better long-term learning than two sessions occurring back-to-back on the same day, but only when participants slept in between the two spaced study sessions.

Thus, the processes associated with consolidation (e.g., LTP, protein synthesis, sleep) appear to occur to a greater extent during spacing than massing, and inhibition of these processes appears to result in attenuation of the spacing effect. Although much research has yet to be done to understand the nature of consolidation, theoretical discussions of the spacing effect would benefit by including consolidation as one of its candidate mechanisms. Given the study-phase retrieval account of spacing effects, the related phenomenon of “reconsolidation”—the retrieval-induced reactivation of a memory that renders it labile and vulnerable to change (Dudai, 2006)—might offer additional theoretical insights.

### 2.26.3 Schedules of Spacing for More Than Two Presentations

Some studies of the spacing effect have included more than two presentations of items. In these designs there are typically two spacing gaps – the time between the first and second presentation, and the time between the second and third presentation. These intervals can be uniform such that equal spacing gaps separate the occurrence of all three presentations or nonuniform such that the spacing gap between the first and second presentation is longer or shorter than the spacing gap between the second and third presentation.

Like many studies of the spacing effect, studies that have explored uniform versus nonuniform spacing gaps have been conducted over relatively brief intervals of time, with spacing gaps on the order of seconds or minutes. These studies show that items repeated three or more times at spaced intervals are better retained than items repeated the same number of times at massed intervals (Carpenter and DeLosh, 2005; Cull, 2000; Cull et al., 1996). Some studies have also found that expanded spacing schedules—with increasingly longer spacing gaps between presentations—produce greater learning than the same amount of spacing distributed across uniform intervals (e.g., Cull et al., 1996; Landauer and Bjork, 1978).

Consistent with a study-phase retrieval account and the desirable difficulties framework, an expanded schedule of spacing might be expected to be superior because it involves the opportunity to retrieve an item soon after its first presentation—at the time when retrieval is likely to be successful and offset the effects of forgetting—combined with the opportunity to retrieve the item again after a longer time interval when retrieval is more difficult but still successful. Uniform intervals, on the other hand, may involve too long a spacing gap between the first and second presentation of an item, running the risk that the earlier occurrence of that item will have been forgotten by the time of the second occurrence.

In studies comparing expanded versus uniform intervals, uniform spacing has produced equal, and sometimes better, performance than expanded spacing (Balota et al., 2006; Carpenter and DeLosh, 2005; Cull, 2000; Karpicke and Bauernschmidt, 2011; Karpicke and Roediger, 2007, 2010; Logan and Balota, 2008). However, other studies have shown that the superiority of an expanded spacing schedule may depend on the presence of critical factors, such as the time intervals involved in the first two retrieval attempts (Maddox et al., 2011). Also Vlach et al. (2014) recently found that expanded spacing led to better performance than uniform spacing in a category induction task, but only when the final test was delayed by 24 h and not when it was given immediately. Storm et al. (2010) also found that retrieving information from a text passage at expanded spacing gaps, relative to uniform spacing gaps, led to superior recall of the passage 1 week later, but only under conditions in which interfering information was presented in between the retrieval attempts. Thus, consistent with the logic of the expanded spacing technique, it appears that expanded spacing may be particularly effective for protecting against forgetting, especially under interfering conditions that render it difficult to keep information active in memory.

Along these lines, Gerbier et al. (2015) reasoned that brief time intervals (i.e., spacing gaps of only seconds or minutes) may not be ideal for exploring the benefits of expanded spacing, as study-phase retrieval may not be particularly challenging across these brief delays and the short spacing gap associated with early stages of expanded retrieval might actually introduce the counterproductive effect of deficient processing. Gerbier et al. presented French-pseudoword pairs three times over several days according to an expanded schedule (first on Day 1, then Day 2, then Day 13) or a uniform schedule (first on Day 1, then Day 7, then Day 13) and found that the expanded schedule produced superior retention of the word pairs, particularly when retention was tested after longer intervals (i.e., 6 or 13 days, compared to only 2 days). These results are consistent with those of other studies that have presented material in expanded versus uniform fashion over the course of several days (Gerbier and Koenig, 2012; Tsai, 1927). However, the expanded spacing benefit appears to be sensitive to multisession designs involving *presentation*, and not *retrieval*, of to-be-learned materials, as similar studies using repeated testing over multiple days have revealed no benefits for expanded versus uniformly spaced retrieval (Cull, 2000; Kang et al., 2014; Kuepper-Tetzel et al. 2014b).

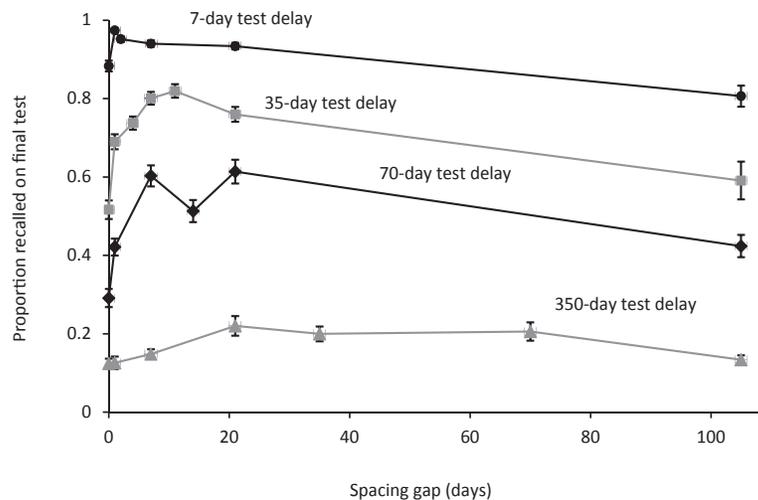
## 2.26.4 Optimal Spacing Gaps

A wealth of research has demonstrated that spacing benefits learning. But how much spacing is optimal? As we have seen, in studies manipulating spacing over relatively short intervals of time, longer spacing gaps do not always yield better memory retention (Appleton-Knapp et al., 2005). The same is true for studies that have manipulated spacing over longer intervals of time on the order of days or weeks. In one demonstration of long-term spacing benefits, Bahrick (1979) found that participants retained Spanish-English vocabulary translations better after 1 month if they completed several learning sessions spaced apart by 30 days compared to 1 day. However, Verkoeijen et al. (2008) observed a quite different result. In their study, students' memory retention of a text passage was better after reading the passage in each of two sessions that were separated by 4 days compared to 3.5 weeks.

In a thorough investigation of the effects of different spacing gaps, Cepeda et al. (2008) set up an online learning environment to teach participants the answers to several obscure trivia questions. After learning these answers through a series of quizzes followed by feedback, participants completed another learning session that involved recalling the answer to each trivia question again, followed by feedback consisting of the correct answer. Thus, each participant completed two learning sessions. These learning sessions were separated by either 0 days (i.e., they occurred in the same session) or one of several spacing gaps ranging from 2 days to 105 days. After completing the two learning sessions, all participants then completed a final test over the same trivia facts after a test delay of 7, 35, 70, or 350 days following the last learning session. Participants were randomly assigned to one of the 26 combinations of spacing gap and test delay.

The results of Cepeda et al.'s (2008) study are presented in Fig. 2. These results show that the spacing gap that produces the best retention depends on the test delay. Longer spacing gaps produce better retention than shorter spacing gaps if the final test is administered after a long delay, whereas the opposite is true if the final test is administered after a shorter delay.

The data in Fig. 2 indicate that the spacing gap producing the best retention depends upon the test delay. When retention is tested after 7 days the optimal spacing gap is 1 day, but when retention is tested after 35 days the optimal spacing gap is 11 days, and so on. Other studies have confirmed the finding that the optimal spacing gap grows larger as the test delay increases (Balota et al., 1989; Cepeda et al., 2009; Kuepper-Tetzel and Erdfelder, 2012; Rawson, 2012; see Glenberg, 1976 for a demonstration



**Figure 2** Recall of facts in [Cepeda et al. \(2008\)](#). Participants learned 32 trivia facts across two sessions that were separated by a spacing gap of either 0, 1, 2, 4, 7, 11, 14, 21, 35, 70, or 105 days and then completed a final test over those facts after a test delay of either 7, 35, 70, or 350 days. The ideal spacing gap depended upon test delay, in that relatively short spacing gaps (e.g., 1 day) produced the best recall after relatively short test delays (e.g., 7 days), whereas longer spacing gaps (e.g., 21 days) produced the best recall after longer test delays (e.g., 70 days).

of this effect with very short time intervals). In [Cepeda et al.'s \(2008\)](#) study, the optimal spacing gap ended up being a ratio of the test delay, such that spacing gaps equaling about 10–20% of the test delay produced the best learning.

### 2.26.5 Spacing and Inductive Learning

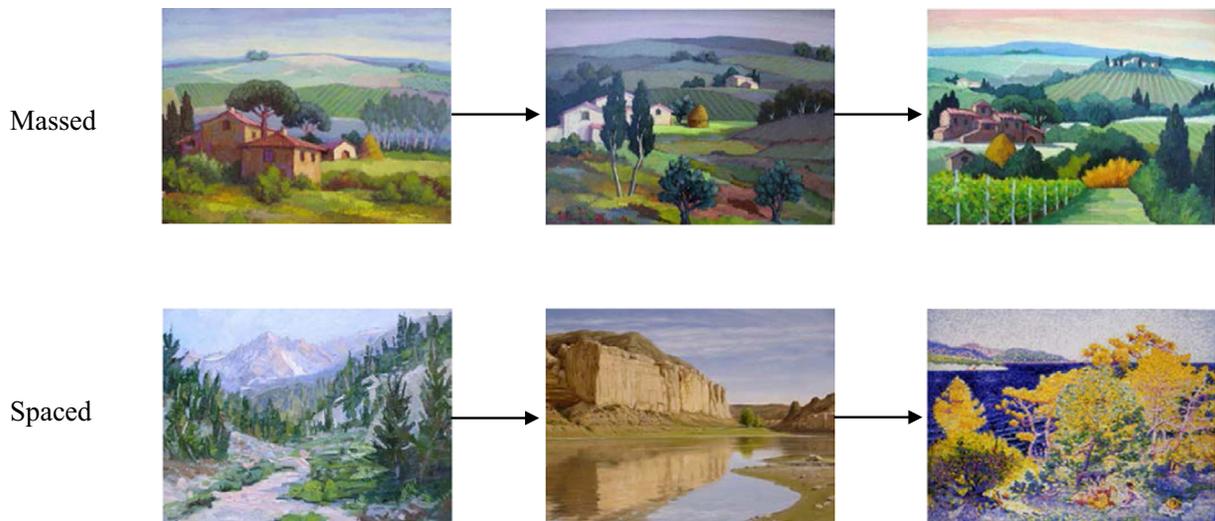
Most of the literature on spacing effects has involved measures of memory for the same, or highly similar, information that was repeated in massed versus spaced fashion. We know much less about the effects of spacing on a learner's ability to extract general rules and categories that are not identical to the information learned. Recent research has begun to address this topic by presenting multiple exemplars from a category in a way that is either massed—such that all exemplars from one category are presented back-to-back—or spaced such that exemplars from all categories are mixed together.

[McDaniel et al. \(2013\)](#) explored spacing effects in a mathematical function learning task in which participants learned 20 pairs of x-y values representing a V-shaped function. To learn the function, participants were shown one of the input values of x (e.g., 117) and had to guess the correct output value of y (e.g., 40) before receiving feedback of the correct answer. In the massed condition, each of the input values was presented five times while alternating with another input value to ensure near-immediate repetition of each input value (e.g., participants saw 103 and had to guess the y value, then they saw 111 and had to guess the y value, followed again by 103, then 111, etc.). This entire sequence was then repeated so that each input value occurred a total of 10 times. In the spaced condition, on the other hand, each of the 20 input values was presented once, in randomized order, across 10 blocks. On a later test over the learned pairs, as well as never-before-seen pairs that fell inside and outside of the learned range, participants performed better if they had learned the pairs via spaced presentation compared to massed presentation.

Recent research has also explored the effects of spacing versus massing on learning the artists associated with various painting styles. [Kornell and Bjork \(2008\)](#) presented participants with a number of example paintings by each of several artists (e.g., Judy Hawkins, Georges Braque, Bruno Pessani, etc.). The order of presentation was either massed such that all of the paintings by one artist appeared before any paintings from another artist appeared, or it was spaced such that two paintings from the same artist never appeared back-to-back (see [Fig. 3](#)). On a later test in which participants were shown never-before-seen paintings by the same artists, they were better at identifying the artists of the new paintings if they had seen the previous examples via spaced presentation compared to massed presentation.

Subsequent research has replicated the spacing effect in category induction tasks using similar types of paintings to the ones used by [Kornell and Bjork \(2008\)](#) (e.g., [Kang and Pashler, 2012](#); [Kornell et al., 2010](#); [Verkoeijen and Bouwmeester, 2014](#); [Zulkipli and Burt, 2013](#)), as well as other visual discrimination tasks such as learning to classify bird species ([Wahlheim et al., 2011](#)). It has also been shown that spaced presentation of case studies representing particular psychiatric disorders enhances learning of the patterns and symptoms associated with those disorders, facilitating diagnoses of never-before-seen case studies ([Zulkipli et al., 2012](#)). Spaced presentation has also been more effective than massed presentation in facilitating children's learning of the categories for novel objects ([Vlach, 2014](#); [Vlach et al., 2012, 2008](#)).

In some of these studies, spaced presentation was manipulated by mixing up the order in which stimuli from different categories occurred. In this way, the spacing gap between two stimuli from the same category was filled by stimuli from different categories. In a different line of research, this type of *interleaved* schedule has been shown to produce learning benefits beyond a blocked (i.e.,



**Figure 3** Example paintings used in the study by Kornell and Bjork (2008). Participants saw either consecutive presentations of paintings by the same artist (top panel, massed) or consecutive presentations of paintings by different artists (bottom panel, spaced) in which no two paintings by the same artist occurred back-to-back. After learning several paintings in massed versus spaced presentation, participants were better at classifying never-before-seen paintings by the same artists for those paintings they had learned through spaced presentation compared to massed presentation.

massed) schedule in which all instances of a given category are presented back-to-back (Carpenter, 2014; Rohrer, 2012). Benefits of interleaving have been shown to occur even when the degree of spacing is held constant (e.g., through simultaneous presentation of stimuli from same vs. different categories, Kang and Pashler, 2012), suggesting that the effects of spacing and interleaving may not be one in the same. It has been proposed that interleaving benefits learning through promoting attention to key differences among the stimuli from different categories that are otherwise easily confused (Rohrer, 2012). In support of this discriminative contrast hypothesis, Birnbaum et al. (2013) found that contiguous interleaved presentation of stimuli from different categories (different bird and butterfly species) produced better category learning than spaced presentation that contained filler material in between the stimuli from different categories.

Further research has shown that the benefits of interleaved presentation may depend on the nature of the categories being learned. Interleaving tends to benefit learning of categories that are easily confused with one another, such as different artists' paintings that share similar surface features (Kornell and Bjork, 2008), different bird species that might share physical features (e.g., color) that are not diagnostic of species (Wahlheim et al., 2011), or the appropriate mathematical procedure to apply to a problem (Rohrer and Taylor, 2007; Taylor and Rohrer, 2010). Thus, when between-category similarity is high, interleaving examples from different categories facilitates category learning by highlighting the unique aspects of the stimuli that are diagnostic of category membership. When between-category similarity is low, however, there is some evidence that interleaving does not facilitate learning, and might even produce inferior learning to blocking (e.g., Carpenter and Mueller, 2013; Carvalho and Goldstone, 2014, 2015a; Goldstone, 1996; Zulkiply and Burt, 2013). In this case, it is not the differences between categories but rather the stimuli within each category that need to be learned, and blocking (i.e., massing) draws attention to the commonalities among stimuli within a category and facilitates abstraction of its defining features (see Carvalho and Goldstone, 2015b for a recent review of sequencing effects and category learning). Importantly, this implies that the benefits of interleaving (or spacing) in category induction may depend on category structure. Given that the goal of category learning is to understand both the category itself and how it differs from other categories, it may be that some combination of blocking and interleaving can be applied to achieve optimal abstraction of category knowledge.

### 2.26.6 Spacing and Metacognition

Effective learning can depend greatly upon metacognition – the degree to which learners are aware of their own state of learning and can use this awareness to guide study decisions. Exploring whether learners are aware of the benefits of spacing, and how often they use it, bears importantly on the value of spacing to enhance learning and long-term retention, particularly in practical domains such as education.

Some studies have examined learners' impressions of the effectiveness of spacing by asking them to judge the effectiveness of spacing for helping them learn. For example, at the end of the test phase in the study by Kornell and Bjork (2008), participants were reminded of the procedure for massing versus spacing and asked "Which do you think helped you learn more, massed or spaced?" (p. 587). This and other studies (see Birnbaum et al., 2013; Zulkiply and Burt, 2013) have shown that participants learn better from spacing, but they often believe they learned better from massing – with 78% of participants in Kornell and Bjork's study indicating that they learned as well or better from massing compared to spacing, and 67% of participants in Birnbaum et al.'s study

indicating that they learned better from massing compared to spacing. Kornell et al. (2010) found that the tendency to favor massing as the more effective strategy occurred in both younger and older adults, with 81% and 96% of these participants, respectively, indicating that massing was as effective or more effective than spacing.

Similar findings have occurred in studies measuring episodic and procedural memory. In a study comparing the learning of GRE vocabulary via spacing versus massing, Kornell (2009) found that 90% of participants learned the vocabulary words better through spacing, but 72% of participants believed that they learned them better through massing. In a study by Logan et al. (2012) in which participants were asked to estimate their future recall of words presented via massing versus spacing, participants overestimated their performance to a greater degree for the massed items compared to the spaced items (Experiment 1; see also Zechmeister and Shaughnessy, 1980). This pattern held even when participants were given experience learning items via spacing versus massing (Experiment 2), and after being directly informed of the benefits of spacing (Experiment 4). Consistent with this pattern of results, Simon and Bjork (2001) found that although participants learned a motor sequence task more effectively through spacing than through massing, participants' judgments of the effectiveness of each technique throughout the learning phase consistently favored massing.

Another way to explore metacognition and spacing is to measure the way in which participants engage with spaced versus massed items during learning. When given the option, do learners choose to space their study? This question was first explored by Son (2004), who presented participations with word pairs for 1 s each and then asked them to make a judgment of learning (JOL) indicating their confidence that they would recall the item on a future test. Participants were then given the option to study the item again immediately (massed), study it again at the end of the list (spaced), or not study it at all. The results indicated that participants were more likely to choose spaced study if they considered the item well learned (i.e., gave it a higher JOL), and more likely to choose massed study if they considered the item not well learned (i.e., gave it a lower JOL).

Under slightly different conditions in which participants were given longer presentation time per item (5 s per item) and had to allocate half the items to spaced and massed restudy without choosing an option to not study further, Benjamin and Bird (2006) found, contrary to Son (2004), that participants allocated the more difficult items (i.e., objectively more difficult items that also received lower JOLs) to spaced restudy and the easier items (i.e., objectively easier items that also received higher JOLs) to massed restudy. Follow-up work by Toppino et al. (2009, Experiment 1; see also Pyc and Dunlosky, 2010) showed that participants were more likely to allocate massed restudy to more difficult items under conditions of brief presentation durations (similar to Son's results) and spaced restudy to more difficult items under conditions of longer presentation duration (similar to Benjamin and Bird's results). Toppino et al. (Experiment 2) further showed that under brief presentation durations, the tendency to choose massed restudy for more difficult items likely reflects deficient encoding (i.e., more difficult words tend to be longer and less common than easier words, requiring more time to read), such that participants wish to see these items again immediately because they did not fully perceive them on the first presentation. Consistent with this interpretation, Toppino and Cohen (2010, Experiment 1) found that item difficulty was associated with an increased tendency to choose massed restudy under conditions of brief presentation in which the more difficult items were longer and less common (the same result as Son, 2004). However, under conditions in which difficulty was associated with the strength of association between the two words but length and frequency (which would affect speed of perception) were controlled, the opposite result was observed in that more difficult items (i.e., cue-target pairs with weaker associative strength) were associated with an increased tendency to choose spaced restudy (the same result as Benjamin and Bird, 2006). Additional support for this *degraded perception hypothesis* was provided by Ariel et al. (2014), who used eye tracking technology and found that stimulus targets that received no fixations were more likely to be chosen by participants for massed restudy than for spaced restudy.

Thus, when given sufficient time to perceive the items, participants appear to allocate spaced restudy to the more difficult items. Why might this be? After allowing participants to choose spaced or massed restudy of list items, Toppino and Cohen (2010, Experiments 2 and 3) included a questionnaire asking participants to list the reasons for their choices. The majority of participants (84%) reported choosing the strategy that they thought would be more effective for learning the more difficult items. This finding is consistent with the idea that participants are aware of the benefits of spacing and use it to learn the items that are most difficult and thus require the most effective strategy.

How can these findings be reconciled with the studies showing that participants' confidence in their own memory is lower for spaced items relative to massed items (e.g., Kornell and Bjork, 2008; Simon and Bjork, 2001)? Such findings would seem to suggest that participants have more faith in massing, relative to spacing, as an effective learning strategy. Studies have shown, however, that metacognitive monitoring can be separated from metacognitive control. Factors that influence one's beliefs about effective study techniques can be different from factors that influence one's perceived sense of the effectiveness of an experienced technique. Choosing to space one's study on the grounds that spacing is believed to be more effective than massing reflects a belief-based decision, whereas making a judgment about how well learned a previously studied item is can reflect influences from subjective heuristics such as processing fluency or retrieval accessibility. Indeed, recent studies have shown that belief-based metacognitive decisions can be independent from subjective experiences based on *fluency*, the subjective sense of how easy it is to process an item during learning (Mueller et al., 2013, 2014, 2016). Learners' tendencies to be more confident in their learning of previously studied massed items over spaced items likely reflect the increased ease-of-processing, or fluency, associated with massed items. Relative to the intermittent occurrence of spaced items, the immediate repetition of massed items creates a sense that they are readily accessible and have been well learned (see Finn and Tauber, 2015 for a review of fluency effects associated with massing and other memory strategies).

In support of this view, some studies have shown that when learners are allowed to pace their own study of massed versus spaced items, they spend less time on the second occurrence of a massed item than on the second occurrence of a spaced item (Shaughnessy

et al., 1972). As processing time has been interpreted as a measure of subjective fluency—with shorter processing times reflecting greater perceived fluency during encoding (Mueller et al., 2014)—these results suggest that participants experience a greater sense of fluency associated with massed items than with spaced items. Fluency has been shown to be positively correlated with confidence in learning (Carpenter and Olson, 2012; Schwartz, 1994), which could account for the finding that massed (i.e., more fluent) presentations relative to spaced (i.e., less fluent) presentations lead to greater confidence, but not necessarily greater accuracy, in one's own learning.

Metacognitive decisions can reflect a number of factors, including one's beliefs about learning, transient subjective influences such as fluency, and learners' motivation, priorities, and experiences. Whether or not learners choose to space their study, and under what circumstances, is an important topic that deserves further research. Particularly in real-world learning, the frequency with which students distribute their study time has critical importance for educational achievement. In the last section of this chapter, a natural and critical application of research on the spacing effect is discussed that has long been overdue—applications of spacing to enhance learning in authentic educational settings.

### 2.26.7 Spacing Effects in Authentic Educational Settings

Hundreds of studies on the spacing effect have been conducted since the seminal work of Ebbinghaus in 1885. The vast majority of these studies have been conducted in the laboratory using spacing intervals on the order of seconds or minutes. Fewer studies have used spacing intervals on the order of days or weeks, and fewer still have used ecologically valid spacing intervals in realistic educational settings such as classrooms.

The robust benefits of spacing and its relatively straightforward applicability would seem to render it a highly valuable principle that can be implemented in educational curricula to enhance student learning (e.g., see Roediger and Pyc, 2012). Despite the straightforward applicability and the need for improving educational outcomes, however, the last several decades have witnessed slow progress in conducting field studies to establish the effectiveness of spacing in authentic educational environments. The need for this type of research was emphasized by Dempster (1988) nearly 30 years ago in a paper titled "The spacing effect: A case study in the failure to apply the results of psychological research." Dempster discussed nine possible impediments to the implementation of spacing to improve educational outcomes and argued that "the most serious of the plausible impediments to the application of the spacing effect is the paucity of impressive classroom demonstrations of the phenomenon" (p. 632).

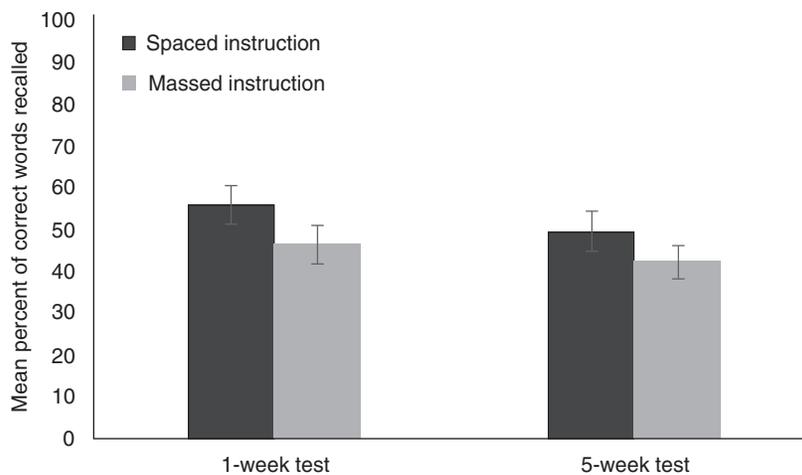
At that time, a handful of studies conducted in classrooms had revealed that spacing appeared to be effective for enhancing students' learning of their course material. Reynolds and Glaser (1964) explored middle school students' learning of biology terms and definitions relating to mitosis. Students learned these terms and definitions during class and reviewed them within a single class period (massed), or reviewed them over two subsequent class periods interspersed with biology terms on other topics (spaced). A test over the terms given 10 days after the last review revealed higher performance for students who completed the spaced reviews compared to the massed reviews. Fishman et al. (1968) explored fifth graders' learning of computerized spelling drills in which the words were presented for practice three times within a session on the same day (massed) or once per day every 2 days (spaced). Students' later spelling of the words was better for words that received spaced training compared to massed training, and this was true for a test given 10 days, and again 20 days, after the end of training. Similarly, Bloom and Shuell (1981) found that high school students learned French vocabulary better when they received instruction in three sessions consisting of 10 min each across three consecutive days (spaced), compared to a single session of 30 min (massed). Rea and Modigliani (1985) had third-grade children learn multiplication facts and spelling lists by presenting a list of the to-be-learned items, one at a time ( $8 \times 5 = 40$ ) and then testing the children over each one ( $8 \times 5 = ?$ ). When the presentation and test for any one item were separated by a few other items (spaced), children retained the information better than when the presentation and test for the same item occurred back-to-back (massed). Gay (1973) further found that eighth-grade students retained mathematics rules best when they completed reviews of the rules 1 and 7 days after learning, compared to 1 and 2 days after learning.

Despite these promising results, however, classroom studies of the spacing effect have been slow to emerge since Dempster's (1988) call to action, and the majority of the research on spacing continues to be laboratory based. However, recent years have witnessed a rather sizable increase in the number of spacing effect studies conducted in authentic educational contexts that include educationally realistic spacing gaps, a range of learning materials, and diverse student populations.

#### 2.26.7.1 Studies of the Spacing Effect in Classrooms

Studies on vocabulary acquisition in school children have shown that spacing facilitates the retention of new words more effectively than massing. In a study by Goossens et al. (2012), third-grade children learned new vocabulary words by receiving instruction (definitions, followed by examples and questions over the words' meanings) three times on 1 day (massed), or once across 3 consecutive days (spaced). Final tests given 1 week and 5 weeks after the final learning session revealed that the meanings of words learned through spaced instruction were retained better than the meanings of words learned through massed instruction (see Fig. 4).

Along similar lines, Sobel et al. (2011) had fifth graders learn new vocabulary words through in-class exercises that involved learning the word's definition and using it in a sentence. These in-class exercises occurred in two sessions that were either scheduled back-to-back within the same class period (massed), or on two different days 1 week apart (spaced). A final test over the definitions given 5 weeks after the second session revealed superior retention of the definitions of words that were learned in the spaced



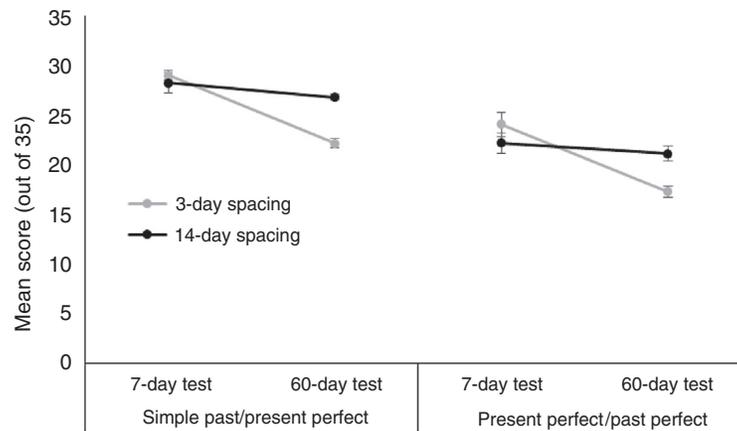
**Figure 4** Final test recall of new vocabulary words in the study by Goossens et al. (2012). Children learned new words via spaced instruction (spread across 3 days) or massed instruction (concentrated into the same day), and then completed tests over the words 1 week and 5 weeks later. Spaced instruction led to significantly greater memory for the definitions of new words, independent of whether the test was administered at 1 or 5 weeks. Error bars represent standard errors.

condition compared to the massed condition. Kuepper-Tetzel et al. (2014a) had sixth grade students learn new vocabulary words via two learning sessions (consisting of studying the German-English word pair and then completing tests to remember the meaning of the English word) that occurred on the same day (massed), or were separated by 1 day (short spacing gap) or 10 days (long spacing gap), followed by a final test (both free and cued recall over the word pairs) either 7 or 35 days after the last learning session. Retention was best for material learned at short and long spacing gaps compared to material that was massed. Furthermore, when retention was tested after 7 days, the 1-day spacing gap was best for learning, and when retention was tested at 35 days, both the 1- and 10-day spacing gaps were best.

Other studies have found that spacing facilitates the learning of different language acquisition skills. In a study by Ambridge et al. (2006), primary school children learned grammatical rules through interactive instruction and examples that consisted of 10 trials presented all in one session (massed) or 2 trials per day for five consecutive days (spaced). A test over the rules at the end of training revealed that children who learned the rules through spaced practice significantly outperformed children who learned them through massed practice. Riches et al. (2005) demonstrated that spacing of instruction on language skills can benefit the learning of children with specific language impairments (SLIs). In their study, 5- to 6-year-old children with SLI learned novel verbs by receiving several exposures to an experimenter acting out the verb (e.g., bouncing an object on the floor). These exposures occurred all on the same day (massed) or spread over 4 days with one-fourth of the exposures occurring on each day (spaced). Immediately after the sessions, children were shown an example of the experimenter acting out the verb and were asked to name the verb. Children were able to produce more correct names of the verbs when they had been trained with the spaced procedure than with the massed procedure. Seabrook et al. (2005, Experiment 3) explored learning of phoneme-grapheme correspondence (i.e., letter-sound matchings) and pronunciation of regular words in first-grade children. Children received three 2-min sessions per day (spaced) or one 6-min session per day (massed) for 2 weeks. Lessons were delivered by the regular instructor and consisted of demonstration of the pronunciations followed by pronunciation practice by the children. Upon completion of the lesson all children were later tested on their knowledge of the letter-sound correspondence and pronunciation of regular words containing the letter-sound matchings from the lessons. Compared to their scores on a pretest measuring reading skills prior to the lessons, the group that received spaced instruction showed significantly greater improvement in these skills than the group that received massed instruction.

In studies with adult learners, spacing has been shown to improve the learning of grammatical rules. In a study by Miles (2014), undergraduate students learning English as a second language learned English grammar rules via three classroom sessions that occurred all on the same day (massed) or on one session per day across 3 days (spaced). All students received a test over the grammar rules at the end of training, and again after 5 weeks. Results revealed that although spacing was not always advantageous on the immediate test following training, on the 5-week delayed test those students who learned the rules through spacing outperformed those who learned them through massing. In a semester-long study by Bird (2010), adult learners of English learned English grammar rules through studying and correcting example sentences focusing on past tense rules (e.g., "I have seen that movie last week"). Students completed these activities in class either every 3 days (short spacing gap) or every 14 days (long spacing gap) during the course of the semester. A later test over the grammatical rules occurred 7 days or 60 days after the final learning session. Similar to the study by Miles, the 7-day test revealed no significant differences in performance as a function of spacing; however, the 60-day test revealed significantly better retention of the grammar rules learned through 14-day spacing gaps compared to 3-day spacing gaps (see Fig. 5).

There are at least two studies showing that spacing improves students' learning of material from their mathematics courses. Schutte et al. (2015) had third-grade students learned math facts via four 1-min practice drills completed back-to-back (massed),



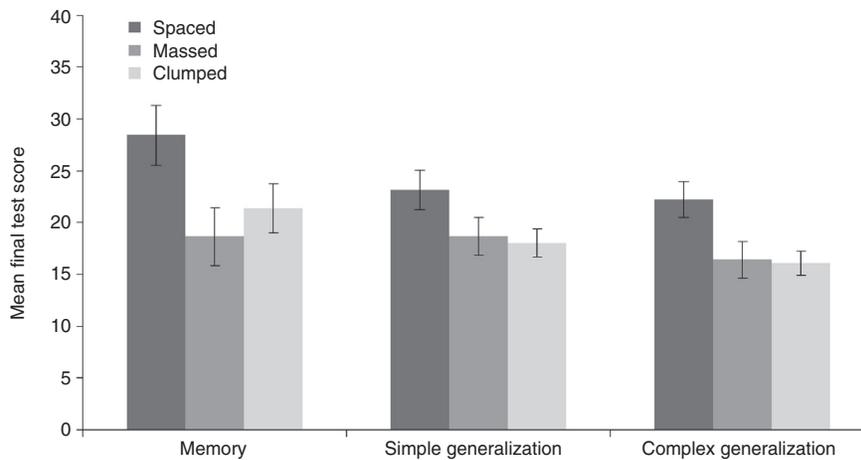
**Figure 5** Final test performance in the study by Bird (2010). Adult learners of English learned grammatical rules by completing exercises in class every 3 days (3-day spacing) or every 14 days (14-day spacing), and then completed tests over the grammatical rules after 7 and 60 days. Although no spacing effect emerged on the 7-day test, on the 60-day test the 14-day spacing condition led to superior performance over the 3-day spacing condition. Error bars represent standard errors.

two 1-min practice drills completed twice, separated by about 3 h ( $2\times$  per day spaced), or four 1-min practice drills separated by about 2 h ( $4\times$  per day spaced). Students practiced these 4-min drills daily across 18 consecutive days. A final test over the facts was given at the completion of the lessons, and again after 10 days. On both the immediate and 10-day delayed test, the  $4\times$  spaced group performed the best, followed by the  $2\times$  per day spaced group, and then the massed group. In a study by Yazdani and Zebrowski (2006), high school students learned geometry principles by completing problems that pertained to each day's lesson (massed) or by completing problems that pertained to each day's lesson combined with problems from previous lessons (spaced). Standardized tests of geometry proficiency were administered as pre- and posttests, and again after 6 weeks. Students who completed spaced exercises showed greater pre- to postgains than students who completed massed exercises, and also scored higher on both the immediate posttest and the 6-week delayed test.

Evidence is also accumulating that spacing can facilitate young children's retention and transfer of scientific concepts. In a study by Vlach and Sandhofer (2012), elementary school children learned scientific information about food chains via four lessons given on the same day (massed), two lessons each given on two consecutive days (clumped), or one lesson given on each of four consecutive days (spaced). Lessons focused on teaching children the scientific concepts associated with food chains, such as the tendency for larger animals to eat smaller animals, and for the number of species to increase when there is more for them to eat. Children learned these concepts in the context of a particular biome (e.g., arctic, desert, ocean, grassland, or swamp), and then 1 week after the last session they were given questions to assess their generalization of the concepts to a biome that they had *not* learned about (e.g., if children learned that snakes eat rats in the grassland biome but did not learn about the desert biome, they might be asked the question "Which of these living things does the scorpion eat: a fox, lizard, beetle, or cactus?"). Scores on this test revealed significantly higher performance for children who received spaced instruction than for children who received clumped or massed instruction. Using a similar design, Gluckman et al. (2014) had first- and second-grade children learn scientific concepts associated with food chains via massed, clumped, or spaced schedules. A final test given 1 week after instruction revealed higher performance for children who received spaced instruction than for children who received clumped or massed instruction, and this applied to memory tasks (e.g., "Bigger animals typically eat \_\_\_\_ animals") as well as simple generalization tasks (e.g., "What does the frog eat?") and complex generalization tasks (e.g., "Let's say that all the frogs get captured and taken away by hunters. What happens to the number of turtles? Does it go up, down, or stay the same?") (see Fig. 6).

Other classroom studies have observed benefits of spacing in a variety of materials and age groups. In a study by Randler et al. (2008), seventh-grade students in biology learned about ecology of the water lily by completing a lesson consisting of instruction and hands-on experiments that was either delivered on the same day in a single 180-min session (massed) or scheduled in four segments consisting of 45 min each, delivered once a week across 4 weeks. A posttest administered after the completion of instruction revealed higher scores for the students who completed the 45-min segments compared to the single 180-min lesson. Carpenter et al. (2009) explored middle school students' retention of information learned in their US history class as a function of whether students completed a review of the material 1 week after finishing their lessons over the information (1-week delay) or 16 weeks after finishing their lessons (16-week delay). On a final test over the same information given 9 months later, the 16-week delay group retained the information better than the 1-week delay group. In a similar vein, Kapler et al. (2015) had undergraduate students attend a lecture on meteorology, then complete a follow-up review of the material either 1 day or 8 days afterward, followed by a final short-answer test consisting of both factual and higher-order questions 35 days after the review session. On this test, participants in the 8-day review condition outperformed those in the 1-day review condition on both types of questions.

There is one known study that has explored the benefits of personalized spacing in an authentic educational context. Lindsey et al. (2014) gave eighth-grade students a web-based flashcard-like tutorial to use in learning and reviewing information for their



**Figure 6** Mean final test scores in the study by [Gluckman et al. \(2014\)](#). Elementary school children learned scientific information about food chains via four lessons given on the same day (massed), two lessons each given on two consecutive days (clumped), or one lesson given on each of four consecutive days (spaced). On a final test 1 week after instruction, spaced instruction led to better performance than either massed or clumped instruction for memory tasks, as well as simple and complex generalization tasks. Error bars represent standard errors.

Spanish class. Students used the tutorial throughout the semester to learn 10 chapters of material. The tutorial involved providing English sentences, to which students typed the Spanish translations and then received feedback. Students worked with the tutorial during class, spending about 30 min per chapter that involved both material from that chapter as well as review of previous material. Students received information in either a *massed* fashion – in which the program selected only information from the current chapter, a *generic spaced* fashion – in which the program selected information from the current chapter and also the previous chapter, or a *personalized spaced* fashion – in which the program selected information from the current chapter, as well as each of the previous chapters according to the material that would benefit most from review based on students' past histories of each item that has been studied. Students' knowledge was assessed via two cumulative exams, one at the end of the semester and one 28 days after that. Personalized spaced review led to the highest scores on the immediate test, and the benefit of personalized spaced review was even greater on the 28-day-delayed test, demonstrating a 16.5% advantage over massed review and a 10% advantage over generic spaced review. Results of this study suggest that spacing schedules that are adapted to individual learners—ideally providing review of information right at the point before it would have been forgotten—can produce greater learning gains than standard spacing.

### 2.26.7.2 Studies of the Spacing Effect in Medical Education

Quite recently, a series of studies on medical education has provided evidence that spacing can improve knowledge and skills related to medical practice. In a study by [Kerfoot et al. \(2007a\)](#), medical residents were given online practice questions that were based on materials from a published study program designed to prepare residents for their in-service examinations. Residents either received, via email, a single packet containing 96 questions to study (massed), or they received daily emails containing one or two questions to study (spaced). In the latter case, the review questions sent each day were periodically repeated throughout the course of 27 weeks, such that after being sent for the first time the same questions were sent 1 and 3 weeks later. After the 27-week review period, online follow-up tests (consisting of 32 questions that were contained on the review and also new questions on the same topics) were given at regular intervals ranging from 1 week to 14 weeks. At all follow-up time intervals, the spaced review group significantly outperformed the massed review group. A follow-up study was later conducted ([Kerfoot, 2009](#)) to test residents' knowledge of 60 questions from the review materials that were not included on the final test in the original study. Of the 537 residents from the original study by Kerfoot et al. (2007), 38% were still in residency at the time of the follow-up, half of whom had been assigned to the spaced review and half to the massed review. Performance on the 60-item online test revealed that the knowledge advantage of spaced review over massed review (70.2% vs. 66.8%, respectively) was still apparent after 2 years.

In another study of online spaced review ([Kerfoot et al., 2010](#)), urology residents learned histopathology diagnostic skills in four organs (bladder, kidney, prostate, and testis) through online instruction consisting of multiple-choice questions about a clinical scenario. Using a within-subjects counterbalanced design, residents received either 20 questions at once (massed) over two topics or one question per day (spaced) over the other two topics. In the latter case, each question was repeated 3 times over the course of 16 weeks. A test of retention over all four topics at the end of the 16-week training period revealed a benefit of spaced training over massed training. In a separate study, similar benefits of spaced review delivered through weekly emails (compared to no review sent through email) were observed for third-year medical students' retention of urology knowledge over the course of several months ([Kerfoot et al., 2007b](#)).

[Raman et al. \(2010\)](#) further demonstrated benefits of spacing in a classroom-based study on nutrition. Gastroenterology residents completed a course on nutrition that was taught 1 h per day, once a week, for 4 weeks (spaced), or was taught in one 4-h

block on the same day (massed). A pre- to posttest improvement score in nutritional knowledge was greater for residents who completed the spaced lesson than the massed lesson, and this was true whether the posttest occurred 1 week or 3 months after the completion of the lessons.

Spacing has also been shown to increase proficiency of surgical skills. In a study by Moulton et al. (2006), surgical residents learned to perform microsurgery procedures by completing four training sessions that consisted of video introductions followed by practice over the procedure using synthetic tissue with an expert present who provided feedback. The four sessions were either scheduled all on the same day (massed) or scheduled such that one session occurred per week across 4 weeks. One month after the completion of training, residents performed a procedure on a live, anesthetized rat. Based on ratings from experts who were blind to condition, residents who received spaced training executed more steps correctly than residents who received massed training, and they also received higher overall ratings of global competence (reflecting the expert's confidence in their ability to perform surgery in the operating room).

Using a virtual reality simulator, van Dongen et al. (2011) explored medical students' learning of endoscopic surgery skills. One group trained for 4 h per day over the course of 2 days (massed), one group trained for 1 h per day over the course of 8 days within a 2-week period (spaced), and one group trained for 1 h per day over the course of 8 days within a 4-week period (wide spaced). A final group drawn from the same sample served as a control group and received no training at all. All groups received a posttest immediately after training, and again 2 months later. On both the immediate and 2-month delayed tests, the spaced and wide-spaced groups performed similar to one another and higher than the massed group, with the control group performing lowest.

In a study by Spruit et al. (2015), medical students learned laparoscopic tasks of varying difficulty in a lab setting. Students learned these tasks through three blocks of training, lasting 75 min each, that either occurred on the same day (massed) or occurred on three different days once per week (spaced). Students' skills were assessed via a test administered 2 weeks after the end of training, and again 1 year after training. On both tests, the group that completed spaced training performed the tasks better, and in less time, than the group that received massed training.

Finally, in a study by Mitchell et al. (2011), surgical interns received training over a surgical procedure that consisted of one training session per week for 4 weeks (weekly training) or one session per month for 4 months (monthly training). Interns were assessed on their surgical skills at the end of the fourth training session as well as 4 months later. Interns were assessed by experts, blind to condition, who used checklists to rate them on different procedural components as well as overall competency. Compared to a pretest administered at the beginning of training, both groups showed comparable improvement. Both groups also showed comparable performance on the posttest following training, and similar levels of performance (indicating the skills were still retained) at the 4-month delayed test. This study did not include a massed training session, but did show that training sessions spaced apart by 1 week versus 1 month appear to result in similar performance gains, suggesting perhaps that a time interval of 1 week between sessions is sufficient to engage the benefits of spacing, at least given the final test delays used in this study.

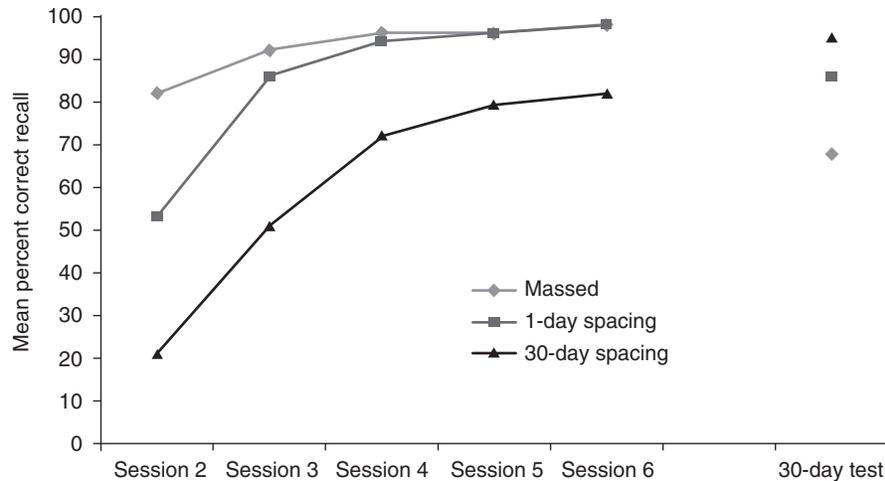
These studies support the notion that spacing can be used to improve learners' retention and transfer of knowledge in real educational environments. Advice to educators, therefore, would be that information should be taught in a spaced, as opposed to massed, fashion. The studies reviewed in this section involve constructing lessons or reviews in a way that affords spaced presentation of the material, such that an instructor provides information from a lesson in a way that is distributed over time or conducts a review at a later, as opposed to an earlier, point in time following initial learning of the material. Additional ways that spacing can be implemented in courses include the method of successive relearning and the use of cumulative exams.

### 2.26.7.3 Other Approaches to Using Spacing: Successive Relearning and Cumulative Exams

The method of successive relearning was pioneered by Bahrick (1979) and is particularly well suited for materials that lend themselves to drill-type practice (e.g., terms and definitions, vocabulary, mathematics rules). In this method, learners first receive a presentation of the material and then engage in recall, followed by feedback, until all of the material can be recalled correctly. In subsequent sessions, the same material is then relearned via tests-with-feedback until it is recalled 100% correctly again. After an initial learning session, Bahrick had participants engage in five more relearning sessions that were either massed (occurred in the same session), spaced apart by 1 day, or spaced apart by 30 days. Although initial performance on the relearning sessions was lowest for the 30-day spacing group (indicating that more forgetting occurred in between sessions), long-term retention on a test given 30 days after learning revealed superior retention for the 30-day spacing group compared to the 1-day spacing group and the massed group (see Fig. 7). A follow-up study 8 years later confirmed that the advantage of the 30-day spacing gap was still apparent (Bahrick and Phelps, 1987).

Other studies have revealed long-term retention benefits of information successively relearned at longer as opposed to shorter spacing gaps (Bahrick et al., 1993; Bahrick and Hall, 2005; Rawson and Dunlosky, 2012). Furthermore, recent data have indicated that successive relearning can be a promising approach for improving educational achievement. In a recent study measuring undergraduate students' learning of information from their introductory psychology course, successive relearning of terms and definitions (delivered via computerized instruction) led to improved exam performance and long-term retention of the concepts compared to engaging in the same number of learning sessions involving pure study (without the recall and feedback associated with successive relearning) of the material (Rawson et al., 2013). Providing opportunities for successive relearning is well within the scope of current technology and could be beneficial for learning course material that can be readily recalled and checked with feedback.

Cumulative exams are another instructional approach that could promote spacing. Repeatedly assessing the same concepts across time provides spaced exposure to the material on the exams themselves and would also seem to encourage students to revisit



**Figure 7** Mean percent recall of Spanish words in the study by Bahrick (1979). Following an initial learning session in which participants recalled the words to 100% accuracy, they engaged in five additional test-with-feedback sessions in which they again recalled the words to 100% accuracy in each session. The means in the graph represent the percent of words correctly recalled on each of the first recall attempts across the five sessions following initial learning. Although 30-day spacing produced slower cumulative learning than massing or 1-day spacing, performance on the 30-day test after training was best for the 30-day spacing group.

the information from previous exams in a spaced fashion as they prepare to be tested over the information again on the next exam. If these assumptions are correct, then cumulative exams should promote better learning of course material relative to noncumulative exams over the same content. In one known study that has addressed this in an experimental paradigm (Lawrence, 2013), students in two different sections of introductory psychology (taught by the same instructor) completed three course exams over the same content prior to a cumulative final exam. The three exams were either noncumulative, containing only information covered since the last exam (in the *noncumulative* section of the course), or they contained information covered since the last exam in addition to 10 questions based on material covered prior to the last exam (in the *cumulative* section of the course). On the final cumulative exam (the same for both sections), students in the cumulative section outperformed students in the noncumulative section (80% vs. 77%, respectively). Furthermore, on a 2-month delayed follow-up test over the concepts (using nonidentical questions from those that appeared on the exams), students from the cumulative section scored higher than students from the noncumulative section. However, this advantage only occurred for the lower-performing students. The higher-performing students showed no significant difference in 2-month delayed follow-up scores between the cumulative and noncumulative sections.

These data suggest that spacing is an effective technique for enhancing learning of course material. Successive relearning and cumulative exams—both of which utilize spacing—appear to be effective for improving students' course performance, although the research exploring these approaches in classrooms is limited. Further data on the effectiveness of these approaches, particularly in authentic educational settings, is encouraged and can shed additional light on whether these methods consistently enhance student learning.

#### 2.26.7.4 Intensive Foreign Language Courses – A Reverse Spacing Effect?

A final set of classroom-based studies that is relevant to spacing involves comparisons between traditional language learning courses and accelerated, intensive courses. Compared to the traditional approach in which a fixed amount of instructional time (e.g., 2–3 h per week) is spread across a typical academic year (e.g., 9 months), condensed courses involve longer periods of instruction per day that are concentrated into a shorter period of time (e.g., several hours per day for 5 months).

According to studies of the spacing effect, shorter periods of instruction distributed over longer periods of time should produce better learning than longer periods of instruction concentrated into shorter periods of time. However, studies on intensive foreign language courses have revealed the opposite pattern. For example, Collins et al. (1999) compared sixth-grade native French students' learning of English via instruction that was *distributed* (where 2 h per day were spent on English instruction across the 10-month school year), *massed* (where most of the day was spent on English instruction across a 5-month period), or *massed plus* (similar to the massed instruction plus out-of-class opportunities to practice English). On a test of English proficiency given toward the end of the instructional period, both the massed and massed plus groups outperformed the distributed group.

In a study by Freed et al. (2004), native English speakers received French instruction through formal courses (lasting approximately 3–4 h per week for 12 weeks) or via an intensive summer immersion program (lasting approximately 17.5 h per week for 7 weeks). Compared to the traditional instruction, the immersion program produced greater gains in oral fluency from the beginning to the end of the program. White and Turner (2005) also found that French students' English proficiency was significantly improved through a 5-month intensive English course (consisting of a total of 400 instructional hours) compared to a traditional 10-month course (consisting of 36 instructional hours).

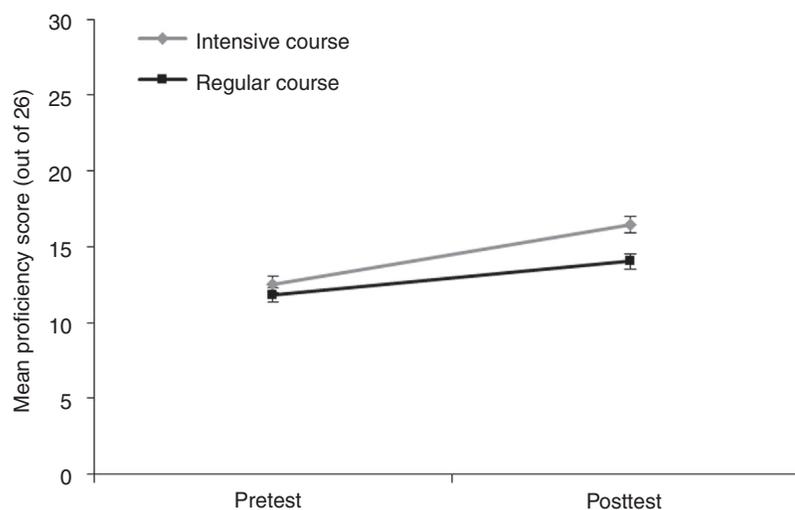
In these studies, however, it is worth noting that the intensive instruction groups received more overall hours of instruction compared to the traditional instruction groups. This confound has been controlled in at least two studies. [Serrano and Muñoz \(2007\)](#) compared native Spanish students' learning of English through three different courses that each consisted of 110 h. The extensive program offered instruction 2 days per week for 2 h each day, over a period of approximately 7 months. The semiintensive course offered instruction 4 days per week for 2.5 h per day, over a period of 11 weeks. The intensive course offered instruction 5 days per week for 5 h per day, over a period of nearly 5 weeks. On a test of English proficiency offered at the beginning and end of each course, students in the intensive and semiintensive courses demonstrated greater gains than students in the extensive course. Similarly, [Serrano \(2011\)](#) compared Spanish students' learning of English through regular courses that involved 110 h of instruction (2-h sessions twice per week) over 7 months, or intensive courses that involved 110 h of instruction (5-h sessions 5 days per week) over 4.5 weeks. Pre- and posttests of English proficiency administered at the beginning and end of the courses again revealed greater gains for students in the intensive course compared to the regular course. These gains were most pronounced for students at the intermediate level of proficiency (see [Fig. 8](#)). Students at the advanced level demonstrated comparable improvement pre- to posttest (about 8% and 9%) for the intensive and regular courses, respectively.

These results appear to contradict the growing number of studies showing spacing benefits in classroom environments. However, it would appear that methodological issues render any firm conclusions premature at this point. Many of these studies involved more overall instruction in the intensive courses than in the regular courses, some involved differences in sampling such that only higher-performing students were eligible to enroll in the intensive courses ([Collins et al., 1999](#)), and it appears that no studies on this topic have included a delayed test of language proficiency (for a discussion of these and other issues, see [Rohrer, 2015](#)). It is possible that language proficiency advantages following regular courses compared to intensive courses may not emerge on immediate tests, but would be more likely to emerge on delayed tests. Indeed, this is the pattern that was observed in the grammar learning studies by [Bird \(2010\)](#) and [Miles \(2014\)](#).

Thus, although it is not immediately clear whether intensive language courses produce greater language proficiency than regular courses when confounding factors are controlled and proficiency is assessed at a delay, the literature on this topic seems to suggest that condensed instruction may lead to better immediate gains than regular instruction. These findings appear to be in line with those of other studies that have sometimes reported no spacing benefit for complex tasks such as air traffic control ([Kanfer et al., 1994](#)) and computerized simulation systems ([de Croock and van Merriënboer, 2007](#)), suggesting that task complexity may play a moderating role in the effects of spacing. It is possible that spacing has different effects on overall language proficiency versus individual components of a language, such as vocabulary ([Bahrick et al., 1993](#)) and grammar rules ([Bird, 2010](#)). From a study-phase retrieval perspective, it could be that complex forms of information needed for overall language proficiency (e.g., understanding of full sentences and spoken information) are difficult to retrieve when spaced at too wide of intervals, such that shorter time intervals in between repetitions may facilitate learning, at least until a certain level of proficiency is reached. More research will hopefully shed light on whether the learning gains from condensed versus regular courses offer data that are consistent with the spacing effect when such factors are considered, or whether they provide an interesting exception that can teach us something new about the mechanisms and applied potential of spacing.

### 2.26.8 Summary and Conclusion

The spacing effect is one of the oldest, most widely studied, and educationally relevant principles of memory to have emerged in modern research on human cognition. The literature on this topic is vast and filled with many theoretically driven studies designed



**Figure 8** Mean score on the English proficiency tests for intermediate students in the study by [Serrano \(2011\)](#). Students participating in intensive courses (5-h sessions, 5 days per week, over 4.5 weeks) showed greater gains in proficiency compared to students participating in regular courses (2-h sessions, 2 days per week, over 7 months). Error bars represent standard errors.

to capture at least part of the ever-elusive answer to the question of why spacing enhances learning. One mechanism alone is not capable of explaining the multitude of spacing effects observed in different types of tasks. Instead, it is more likely that some combination of deficient processing, contextual variability, and study-phase retrieval play unique or integrated roles depending on the circumstances. Emerging data from behavioral and neuroscience studies also point to consolidation as a potential contributor to the advantages of spacing.

The majority of studies on spacing have been conducted in laboratory environments with spacing manipulations carried out on the order of seconds or minutes. However, an increasing number of studies show that long-term spacing effects are also quite prevalent, with spacing gaps on the order of days or weeks producing significant learning gains, particularly at longer test delays. This research suggests that when faced with the practical question of how long to space apart one's study sessions, learners must be aware of how long they wish to retain the information.

Studies comparing more than two study sessions have sometimes found that an expanded spacing schedule produces better learning than a uniform spacing schedule. Although the results over short time intervals are somewhat mixed, recent evidence suggests that expanded schedules may be particularly beneficial in designs involving long-term spacing, and under conditions that promote interference. Given the likely possibility that learners in real-world tasks will engage in more than two study episodes, research on the effects of spacing schedules across three or more study sessions is of educational relevance and deserves further research.

The spacing effect literature is replete with studies measuring direct retention of identical repetitions of stimuli. However, recent research on the benefits of spacing on category induction tasks has shown that spacing of repetitions of the same *type* of stimulus—nonidentical examples belonging to the same category—can facilitate learning of categorical rules and concepts. However, the effects of spacing may depend upon category structure and whether the goal is to learn within-category similarities or cross-categorical differences. Presently, it appears that spacing (particularly if it involves interleaving) promotes learning of cross-categorical differences when those differences are initially hard to detect, but that massing (or blocking) may promote learning of within-category similarities.

Whether or not learners are aware of the benefits of spacing and will utilize it on their own is at present not completely clear. In studies allowing learners to decide what to study next and when, learners often choose to study items later (which promotes spacing), and they tend to choose this option more often for the more difficult items. Other evidence suggests that learners do not appear to be aware of the benefits of spacing, with learners endorsing massing as the more effective strategy even after directly experiencing the benefits of spacing. Recent research on the distinction between metacognitive beliefs and subjective experiences of fluency may be relevant to explaining students' metacognitive patterns associated with spacing.

The benefits of spacing have, until relatively recently, remained a virtually untapped resource for improving learning in educational domains. However, the last several years have witnessed a sizable increase in the number of studies exploring spacing effects in authentic educational contexts, all the way from elementary school classrooms to medical school training laboratories. Spacing effects have been readily observed across these samples and across a variety of subject areas such as science, mathematics, history, language, medical concepts, and even surgical procedures. Although benefits of spacing appear to be robust in these domains, studies of intensive foreign language courses may reveal a different pattern that awaits clarification from further research. The method of successive relearning and cumulative exams are other potential methods of implementing spacing that so far show promising results for enhancing learning outcomes in classes, but current data on these techniques are also limited and will benefit from future research that can provide additional investigations of these techniques in educational environments.

The ever-changing landscape of education, with its increasing reliance on technology, experimental courses, and nontraditional methods of learning, is in continuous need of instructional approaches that can produce consistent and meaningful improvements in educational outcomes. It is hoped that continued efforts will be directed at understanding and applying spacing in educational contexts, toward the goal of optimizing the durability and efficiency of real-world learning.

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*See also:* 2.27 Retrieval-Based Learning: A Decade of Progress.

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