Original Article

Using Spacing to Promote Lasting Learning in Educational Contexts

Promises and Challenges

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Abstract: Spacing repeated study phases across multiple sessions instead of studying and restudying the learning material in one session only is an effective strategy to promote lasting learning. However, most studies demonstrating the spacing effect were conducted in the laboratory, using simple verbal material. Learning in educational contexts differs regarding the complexity and coherence of the learning material and concerning the role of motivational and affective learner characteristics. Studies conducted in educational contexts suggest that the spacing effect is not as robust here. For example, acquiring mathematical skills or nonrepeated, consecutive information does not reliably benefit from spacing. After an overview of studies addressing the spacing effect in the laboratory and in educational contexts, we discuss various open questions that need to be addressed by future research before recommending spacing as a learning strategy to promote meaningful and lasting learning at schools and universities.

Keywords: spacing, lasting learning, desirable difficulties, school learning

Verteiltes Lernen zur Förderung nachhaltigen Lernens und Behaltens in Bildungskontexten. Möglichkeiten und Herausforderungen

Zusammenfassung: Lernen und Wiederholen auf mehrere Sitzungen zu verteilen statt den Lernstoff nur in einer Sitzung zu lernen und zu wiederholen, ist eine effektive Strategie, um nachhaltiges Lernen und Behalten zu fördern. Allerdings wurden die meisten Studien, die einen positiven Effekt des verteilten Lernens berichten, im Labor mit einfachem, verbalem Lernmaterial durchgeführt. Lernen in realen Bildungskontexten unterscheidet sich jedoch vom Lernen im Labor beispielsweise bezüglich der Komplexität und Kohärenz des Lernmaterials sowie der Rolle motivationaler und affektiver Lernermerkmale. Studien, die bislang in Bildungskontexten durchgeführt wurden, legen nahe, dass der Effekt des verteilten Lernens hier nicht so robust auftritt. Beispielsweise profitierte der Erwerb mathematischer Fähigkeiten oder das Aneignen nicht-wiederholter, konsekutiver Information vom verteilten Lernen nicht zuverlässig. Wir geben einen Überblick über Studien zum Effekt des verteilten Lernens im Labor und in Bildungskontexten und diskutieren offene Fragen, die man klären sollte, bevor das verteilte Lernen als Strategie zur Förderung bedeutungshaltigen und nachhaltigen Lernens an Schulen und Universitäten empfohlen werden kann.

Schlüsselwörter: Verteiltes Lernen, nachhaltiges Lernen, wünschenswerte Erschwernisse, schulisches Lernen

Lasting learning denotes the acquisition of knowledge and skills such that they remain retrievable for a long time, that is, for weeks, months, years, or even a lifetime. Lasting learning is a major objective of education for several reasons (see Richter et al., 2022a). First, many situations require profound knowledge that can be easily accessed and applied in a given situation. For example, a person who intends to administer first aid in a traffic accident must instantaneously remember how to create a recovery position or a heart massage; or an adult who provides directions to foreigners in their language must remember foreign language skills from school. Second, lasting knowledge serves as prior knowledge that promotes the acquisition of further knowledge by facilitating the encoding and processing of new information and its integration with existing knowledge (i.e., knowledge as preparation for future learning; Bransford & Schwartz, 1999).

One way to promote lasting learning is to optimize the schedule of the learning and relearning sessions by implementing temporal breaks between sessions. Spacing (also called distributed practice, distributed learning, or spaced review) denotes the distribution of the total learning time across several sessions instead of studying the content in only one session in a massed fashion. Importantly, the total amount of learning time is identical in

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both conditions, the only difference is that breaks in the spaced condition temporally separate the sessions. The interstudy intervals (ISI) can last from a few seconds to days or weeks (Cepeda et al., 2006).

Bahrick's studies on long-term retention provide a good illustration of the spacing effect. In one study (Bahrick, 1979), college students initially learned and later relearned Spanish-English word pairs in six training sessions either in a massed fashion (i.e., all sessions on one day, with a few seconds between each session) or in one of two spaced fashions (i.e., sessions on different days, with an interval of 1 day or 30 days between sessions). A test immediately followed each training session. As expected, cumulative learning across sessions was faster for shorter intervals, whereas longer intervals led to more forgetting during the first training sessions. After another 30 days, a seventh training and test session followed in each condition, yielding a superior performance from participants who had studied with an interval of 30 days before, compared to those who had studied before in a massed session or spaced with a one-day interval. Thus, massed learning benefits short-time learning outcomes but also accelerates forgetting, whereas spaced learning benefits long-time retention. The same students were tested again 8 years later, revealing a clear advantage of students who had learned the vocabulary with long intervals between the sessions (Bahrick & Phelphs, 1987).

These findings can be taken as evidence that spacing learning and relearning sessions are suitable for supporting the acquisition of lasting knowledge. Spacing also seems to be a *desirable difficulty* because it makes the learning process more difficult for the learners, impairs their performance during the acquisition phase, and promotes lasting learning (Bjork, 1994).

The Focus of Previous Research

Studies addressing the spacing effect have often used the same content acquired first and then restudied (e.g., vocabulary). As we outline below, spacing can also include related but nonidentical content in the different sessions (e.g., different calculation tasks that refer to the same principle of written multidigit calculation) or even new, consecutive contents (e.g., two related chapters of a biology textbook). Spacing differs from interleaved learning (see Richter et al., 2022b) because spacing addresses only one learning content at a time, whereas interleaving comprises different but related learning contents that are alternated. Thus, interleaving also involves some kind of spacing for each content but additionally allows for comparing and contrasting the two contents, whereas spacing includes more or less a cognitive break from learning.

The basic idea behind spacing as an efficient learning principle goes back to Ebbinghaus (1885/1964), who in his self-experiments observed that, to achieve a certain mastery level, the spaced repetition of meaningless syllables required less relearning than their massed repetition. Since Ebbinghaus' pivotal observation, hundreds of studies addressing the effect of spacing on learning followed, most of them supporting the assumption of Ebbinghaus (1885/1964). In line with the classification of spacing as a desirable difficulty, many studies further revealed that spacing yields long-term benefits for learning, whereas massing is often more beneficial when the test is administered immediately after the learning phase (e.g., Rawson & Kintsch, 2005).

The spacing effect was demonstrated in different age groups and for different learning contents, including motor skills and verbal skills (for reviews, cf. Cepeda et al., 2006; Lee & Genovese, 1988; Smith & Scarf, 2017). The spacing effect, however, depends on the duration of the interstudy interval. Longer intervals between study sessions often yielded larger benefits for retrieval than shorter intervals (i.e., lag effect; Glenberg, 1976). However, if the interstudy intervals are too long, they may induce too much forgetting and thereby impair retrieval. Thus, an inverted u-shaped relationship between interstudy interval and retrieval performance seems plausible (Verkoeijen et al., 2005). Moreover, longer retention intervals benefit from longer interstudy intervals, even though this relationship is not monotonic (Cepeda et al., 2008).

Most studies addressing the spacing effect were conducted in the laboratory, involving just simple, verbal material like vocabulary or trivia facts (see Wiseheart et al., 2019, for an overview). However, meaningful learning, denoting the acquisition and integration of coherent information in organized mental models and the ability to use this information for drawing inferences and solving problems (Karpicke & Grimaldi, 2012), has not been addressed in these types of studies. Yet, meaningful learning plays an important role in educational contexts in which rote learning and comprehension are desired (see also Richter et al., 2022a).

Theories of the Spacing Effect

Different theoretical accounts have been proposed to explain why spacing study phases promotes lasting learning (see Delaney et al., 2010; Toppino & Gerbier, 2014, for overviews). One explanation refers to the processing of information during learning, which is usually negatively affected the longer a study phase lasts, because the attention and on-task focus of the learner decrease (e.g., Magliero, 1983). This *deficient processing* can be diminished by spacing the study phases and including temporal breaks that allow for the recovery of cognitive resources. Moreover, for the spacing of identical content, spacing presumably promotes deeper semantic processing because the first mental presentation of information has already started to decay after a break, and the delayed, subsequent presentation is therefore not identified as a simple repetition of recent information. The decay elicits a deeper processing attempt by the learner compared to the superficial processing of already familiar information (Rose, 1980). The deficient processing account has received considerable empirical support not only from studies focusing on the learning outcome (e.g., memory performance) but also from studies addressing the neurophysiological mechanisms behind the effect (for an overview, see Toppino & Gerbier, 2014). However, it cannot explain, for example, that the spacing effect is reversed with massing outperforming spacing, when items to be learned are initially presented very rapidly (i.e., for 0.5 s only; Metcalfe & Kornell, 2003).

Regarding the deficient processing account, spacing is assumed to diminish habituation (Hintzman, 1974) and semantic priming effects (Challis, 1993), which in turn increases attention and processing time (Shaughnessy et al., 1972). Semantic priming is a process in which the first presentation of an item evokes the activation of a mental representation that may persist until the repeated presentation of the same item, resulting in less semantic processing. The later the repeated presentation occurs, the more this priming effect diminishes, and the more semantic processing occurs. However, semantic priming can explain neither the spacing effect for perceptual, nonsemantic material (e.g., unknown faces; Parkin et al., 1995) nor the finding that the spacing effect differs for different semantic material (i.e., associated versus repeated items; Hintzman et al., 1975).

Another account that explains the spacing effect is the *variability of the learning context* elicited by spacing. Contextual information is automatically encoded and stored simultaneously with the target information and can therefore be used for retrieving the target information (Estes, 1955, 1959). The changes in the external learning context (e.g., the room) as well as changes in the internal context (e.g., the learner's mood) are assumed to be larger in a spaced than in a massed learning condition. Accordingly, the larger contextual variability during spaced study sessions provides more memory cues that, in turn, facilitate retrieval of spaced studied information (Balota et al., 1989; Glenberg, 1979). However, research has shown that, when spacing involves long lags between the study phases, keeping the learning context constant leads to better learning outcomes than varying the learning context (Toppino & Gerbier, 2014). In addition, although contextual variability can be assumed to be similar for long study intervals (e.g., 28 or 56 days), a better memory performance nonetheless emerges for the longer study interval (Bahrick et al., 1993). Thus, the contextual variability account alone is not sufficient to explain specific characteristics of the spacing effect, such as the lag effect (Glenberg, 1976).

Another approach refers to retrieval evoked when the study phases are separated temporally (i.e., *study-phase retrieval*; Delaney et al., 2010; Thios & D'Agostino, 1976). When study phases are massed, retrieval is not usually necessary because the information is still activated in working memory. However, when the study phases are spaced, each new study phase requires retrieving the content of the preceding study phase. Retrieval during the learning phase is well known for increasing retention, also called the testing effect (for reviews and meta-analyses concerning the testing effect, see Adesope et al., 2017; Roediger & Karpicke, 2006; Rowland, 2014; see also Roelle et al., 2022). The study-phase retrieval account can also explain that longer lags between spaced study phases lead to a better learning outcome. Longer lags make retrieval more effortful, which boosts memory as long as the retrieval attempts are successful (Toppino & Bloom, 2002).

Meta-cognitive accounts have also been proposed to explain the spacing effect. Compared to shorter interstudy intervals, longer intervals allow learners to better adjust their study strategies based on the performance feedback they receive. Accordingly, they might choose strategies that are better suited for longer retention intervals, that is, longer delays between the learning phase and the test phase (Bahrick, 2000). The deficient processing account introduced earlier can also partly be considered a metacognitive account, because learners can actively avoid deficient processing by including breaks in their study process.

Finally, spacing has been proposed to prevent overlearning (Rohrer, 2009), which denotes the phenomenon that items in a set are studied repeatedly even when the learner has already internalized them. Overlearning occurs when a whole block of items is repeated, not only items that are not yet consolidated. As Rohrer (2009) pointed out, compared to massing, spacing reduces the number of overlearning trials because spacing induces forgetting between the learning phases. A smaller number of overlearning trials reduces the ineffective use of study time and makes spacing more efficient, especially when the total learning time is limited.

There is now consensus that no single account can explain the spacing effect. Instead, most researchers assume that the avoidance of deficient processing and study-phase retrieval (Toppino & Gerbier, 2014; but see Küpper-Tetzel et al., 2014, who make a case for the contextual variability account) or contextual variability and study-phase retrieval concur to produce the effect (Delaney et al., 2010; Maddox, 2016; Raaijmakers, 2003; Verkoeijen et al., 2004). In principle, all accounts may contribute to explaining the spacing effect, even though their explanatory value differs, depending on whether the study material involves the pure repetition of a content, related contents, or unrepeated, consecutive contents across the different study sessions.

Effects of Spacing in the Laboratory

Meta-analyses revealed robust medium-to-large spacing effects in laboratory studies (e.g., for verbal learning: Cepeda et al., 2006; Donovan & Radosevich, 1999; Janiszewski et al., 2003; for motor learning: Lee & Genovese, 1988). The spacing effect was obtained for a broad variety of age groups, from infants (e.g., Rovee-Collier et al., 1995) to elderly people (e.g., Simone et al., 2013), and for different learning outcomes that can be categorized into verbal, motor, intellectual (e.g., mathematics, science, literacy), social, and emotional skills (Gagné, 1977, 1984). Medium-to-large spacing effects were established for verbal, motor, and intellectual outcomes (with most studies focusing on verbal materials) and small spacing effects for social and emotional skills (for an overview, see Wiseheart et al., 2019).

Apart from the general spacing effect, laboratory studies also examined whether an optimal lag between the study phases maximizes the learning outcome. One meta-analysis (Janiszewski et al., 2003) revealed a larger spacing effect for longer compared to shorter interstudy intervals (i.e., *lag effect*), whereas another meta-analysis found no such relationship (Donovan & Radosevich, 1999). To delve deeper into the lag effect, several studies focused on the optimal relationship between the interstudy interval (ISI) and the retention interval (RI). As revealed by a comprehensive review (Cepeda et al., 2006), a longer temporal delay between the learning phase(s) and test (i.e., retention interval, RI) benefits from longer delays between the single study phases (ISI), but the assumption of a simple lag effect was not confirmed. Instead, the optimal relationship between ISI and RI follows an inverted u-shaped function, and the optimal ratio between ISI and RI decreases for longer RIs (see also Cepeda et al., 2008; Verkoeijen et al., 2005).

Another factor is the *temporal variability of the ISI* comprised of either fixed, expanding, or contracting intervals between different study phases. Overall, expanding intervals, starting with shorter ISI that become longer for each subsequent ISI, outperform fixed intervals (Cepeda et al., 2006). This finding was reported in one study in which the configuration of ISI and RI were manipulated systematically (Küpper-Tetzel et al., 2014). Results revealed that recall performance after a long RI (i.e., 35 days) benefited to a similar degree from a fixed and an expanding interval, whereas recall performance after a short RI of 1 or 7 days benefitted most from a contracting interval (i.e., starting with long ISI that become shorter for each subsequent ISI). The contextual overlap explained these findings between the learning and test phase, which was assumed to be larger between contracting ISIs and short RIs. Correspondingly, equal or expanding ISIs should provide more contextual overlap with long RIs. However, another study suggested larger spacing effects when an expanding interval was combined with a short RI and a fixed interval was combined with a long RI (Karpicke & Roediger, 2007). To conclude, the results are inconsistent regarding the optimal arrangement of the ISI, as discussed by Balota et al. (2007) for spaced retrieval as one form of spacing.

Why Spacing in the Laboratory Might Differ From Spacing in the Classroom

Given the mainly positive results on the spacing effect for verbatim material in the laboratory, researchers have suggested applying spacing to promote learning at schools and universities (e.g., Dunlosky et al., 2013; Putnam et al., 2016). However, as Dempster (1988) already emphasized, several impediments might hinder the application of spacing in educational contexts. These impediments include the small number of classroom studies on the spacing effect and the lack of these effects in school-like contexts. Interestingly, the situation has not changed much since Dempster's claim.

Whether spacing maintains its effectiveness in classroom contexts remains unclear because many circumstances differ from learning in typical laboratory experiments. First, the learning material used in schools and universities is usually more coherent and more complex than the simple verbal material frequently used in laboratory studies. The material complexity relates to a central goal of education: meaningful learning. Students are expected to acquire not only mere isolated facts but also to comprehend complex phenomena with many interrelations between facts, and to integrate this information with their prior knowledge. A meta-analysis (Donovan & Radosevich, 1999) revealed smaller effect sizes for more complex compared to less complex tasks. More complex tasks were defined by high mental requirements (i.e., mental or cognitive skills and abilities to perform the task), high physical requirements (i. e., physical skills or abilities to perform the task), and high overall complexity (i. e., number of distinct behaviors, decisions, and level of uncertainty when performing the task). Learning word lists, the standard task used in laboratory experiments, represents a less complex task.

Correspondingly, the spacing effect for one particular aspect of intellectual skills – mathematical learning (Gagné, 1977, 1984) – is not as evident, not even in the laboratory, as suggested. Rohrer and Taylor (2006, 2007), for example, taught college students in the laboratory how to solve permutation problems and let them practice this skill in either a spaced or massed manner. In one experiment (2006, Experiment 1), a spacing effect emerged in the test after 4 weeks but not in the test after 1 week. In contrast, in another experiment (2007, Experiment 1) involving the same material and the same ISI (i. e., 1 week), an effect was also found in the test. In another laboratory study that also addressed the solving of permutation problems by university students, no spacing effect occurred, neither in the test after 1 week nor after 5 weeks (Ebersbach & Barzagar Nazari, 2020b). In this study, the ISI was also manipulated, with an interval of 0 (i. e., massed condition, 1 or 11 days between the practice intervals). However, again, no lag effect occurred (see Küpper-Tetzel et al., 2014, for contrary results in their laboratory study). Thus, even in laboratory studies, the spacing effect for mathematical skills seems not very robust. The same holds for examinations of the spacing effect for mathematical skills in educational settings outside the laboratory, as is discussed later.

A second difference between learning in laboratory settings and educational settings is that learning in schools and universities is more strongly affected by the learners' motivational and affective variables. Students in schools and universities usually learn in more flexible and unregulated contexts than in typical laboratory experiments, but their learning requires more self-regulation to varying degrees (Alexander & Green, 2017). Thus, motivational and emotional dispositions and states, which have hardly been examined in research on the spacing effect, might interact with the effect.

Third, learning at schools and universities often occurs in group settings rather than individual learning settings in the laboratory. In sum, it is unclear whether spacing of more complex information and skills, as usually acquired in educational contexts, yields similar positive effects as in the laboratory.

Effects of Spacing in Educational Contexts

As already discussed, many more studies on the spacing effect have been conducted in the laboratory than in the classroom. Many of the classroom studies addressed verbal skills, such as the acquisition of vocabulary (e. g., Sobel et al., 2011), historical facts (Carpenter et al., 2009), or reading skills (Seabrook et al., 2005) and reported positive effects of spacing on long-term retention. However, only a few experiments that included a spacing and a massed learning condition and no further confounding factors were conducted in educational settings with coherent material that went beyond the rote learning of mere words or sentences (see Wiseheart et al., 2019, for an overview). For example, when students acquire the phenomenon of single-cell organisms in biology, they are presented with their structure, their mode of life, their propagation, and their functions in a larger system. Thus, facts are embedded in a more complex representation, involving mutual dependencies and processes that require a deeper understanding and not just superficial processing.

One experimental study in line with the above-mentioned requirements addressed the acquisition of rather complex mathematical skills of third- and seventh-graders (Barzagar Nazari & Ebersbach, 2018). Students first attended an introductory lesson on a mathematical principle from their curriculum (i. e., semiformal multiplication in the third grade; calculating simple probabilities and drawing of tree diagrams in the seventh grade). Thereafter, they practiced the principles in the context of their homework in either a spaced (i. e., all tasks distributed across three consecutive days) or massed fashion (i. e., all tasks on one day). Lasting learning was assessed 1 and 6 weeks after the last practice session. A positive spacing effect was found with seventh-graders in both tests, but the results for third-graders were less clear, with a positive effect after 1 week but none after 6 weeks. This discrepancy among third-graders cannot be explained by low power because the sample size of the study was sufficient. Two speculations could be that the spacing effect in younger age groups lasts shorter. or that other activities interfered with the spacing effect in the long run.

In another study with seventh-graders (Barzagar Nazari & Ebersbach, 2019), the same learning content was used as in the previous study in this age group, but this time students received feedback (i. e., the correct solution) on their practice tasks, and final tests were administered 2 and 6 weeks after the last practice session. The authors found a positive effect of spacing after 6 weeks, with a more pronounced effect for students at a medium performance level than for students on either a low or high performance level. However, they found no spacing effect for the test after 2 weeks. Thus, similar to the spacing effect in the laboratory (e.g., Rohrer & Taylor, 2006), the spacing effect in educational contexts that assessed the acquisition of mathematical skills has not proved to be very robust. Thus, whether spacing should be recommended to teachers and learners remains an open question, especially when the acquisition involves more complex mathematical skills beyond simple facts (such as 2 + 2 = 4).

Outside mathematics, the spacing effect is also not always evident. For example, in a field experiment with college students who reread a text once in a spaced fashion (with 1 week between the readings), Rawson and Kintsch (2005) showed that it benefitted their long-term learning (measured 2 days after study) compared to massed rereading, which excelled over spaced rereading in an immediate test. However, in an experiment with seventh-graders using a biology text that matched the students' curriculum, Greving and Richter (2019) could replicate only the short-term advantage of massed rereading but not the long-term advantage of spaced rereading.

Other studies that revealed a spacing effect in educational settings often implemented no pure massed session (i.e., ISI of 0) but only different kinds of spacing (e.g., shorter versus longer ISI), because the experiments often involved a longer learning period (e.g., one semester or school year). However, such a design addresses the lag effect (Glenberg, 1976) and precludes unequivocal conclusions on the spacing effect in educational settings.

For example, Hopkins et al. (2016) manipulated the spacing of retrieval practice in university calculus courses across one semester. All students completed practice tasks that addressed the target objectives of the lectures in a weekly manner within 48 hours. Students in the "less-spaced" condition completed all tasks that referred to the lectures' content of the same week in this period, whereas students in the "more-spaced" condition completed only a part of the tasks in this period and worked on the other tasks in two other time periods distributed across 3 weeks. Performance was analyzed on exams that assessed the practiced content at the end of the semester and on exams in the following semester. Students in the "more-spaced" condition outperformed those in the "less-spaced" condition on the exam that directly assessed the practiced content and also on the final exam in the subsequent course (for similar findings on learning mathematics, also using different intensities of spaced retrieval instead of comparing the spacing of a pure massed condition, see Lyle et al., 2020; Rickard et al., 2008).

In sum, studies that addressed the spacing effect in educational contexts involving more complex, coherent material are still rare (see Dempster, 1988), and they have not always involved a pure massed condition. Moreover, several open questions (see next section) need to be answered before recommending to teachers and learners the use of spacing.

Open Questions

Does Spacing Benefit the Learning of Complex Content With Coherent Learning Materials?

As outlined earlier, most studies investigating the spacing effect focused on verbal learning with simple materials (e.g., word lists or trivia facts; Wiseheart et al., 2019), which are "less complex tasks" for which larger effect sizes were reported in meta-analyses (Donovan & Radosevich, 1999). However, more research is needed that includes *more coherent learning materials* and *complex content* consistent with the curricula of schools and universities, the goal of which is to promote students' meaningful learning. As outlined earlier, the evidence obtained to date for spacing effects with this kind of material is scarce and inconsistent.

Does Spacing Benefit Comprehension, the Acquisition of Procedural Knowledge, and Transfer?

Another open question refers to the kind of *learning outcomes* augmented by spacing. Related to the previous suggestion of examining the spacing effect for more complex and coherent learning material, the assessment of *comprehension* (e.g., of processes or relationships) as a learning outcome (and not only simple factual knowledge as in many studies) could provide informative results. Comprehension has been mainly investigated in studies examining the spacing effect on reading skills and second language learning (see Kim & Webb, 2022, for a meta-analysis). However, comprehension is also an important aspect in acquiring skills and a deeper understanding of principles and phenomena in, for example, STEM domains (science, technology, engineering, and mathematics), and it is a core component of meaningful learning at large (Kintsch, 1994; Mayer, 2002).

Although ample research has provided evidence for a spacing effect with verbal, declarative information (cf. Janiszewski et al., 2003) and for motor skills (e.g., learning to dribble a basketball, cf. Lee & Genovese, 1988), *procedural knowledge* or other cognitive skills (including skills taught at school) have not gained much attention. An exception is studies on the learning of mathematics in which students learn a certain procedure (e.g., how to solve a mathematical problem), practice it in a spaced or massed manner, and are then tested on the execution of these procedures in problems of the same structure (e.g., Barzagar Nazari & Ebersbach, 2018, 2019; Rohrer & Taylor, 2006, 2007). Future research that clearly separates the learning outcomes to differentially evaluate the spacing effect would be informative. In mathematics, for example, the ability to execute certain procedures in terms of efficiency (i.e., accuracy and speed when solving a problem) could be assessed and the corresponding declarative knowledge as well (e.g., knowing a certain procedure or formula).

The outcome variable of the spacing effect can also be differentiated as *remembering* versus *learning* (Kintsch, 1994), which denotes whether content can be recalled or recognized in terms of rote memory, or whether knowledge of the learning content has been acquired that also can be applied flexibly. The latter is related to *transfer skills*, namely, the ability to apply a procedure to solve related but not identical problems. Transfer skills have largely been neglected in research on the spacing effect (for exceptions, see the review of Smith & Scarf, 2017; for studies with children, see Gluckman et al., 2014; Vlach & Sandhofer, 2012). In one study investigating the spacing effect on transfer, students' homework on the content learned in a statistics lecture was organized in a spaced or massed manner (Ebersbach & Barzagar Nazari, 2020a). This study revealed a benefit of spacing not only for retention but also for transfer performance (for similar findings on transfer abilities, see Kapler et al., 2015, who varied the amount of spacing).

Does Spacing Benefit Learning With Nonrepeated, Consecutive Learning Materials?

Almost all extant studies on the spacing effect used the same material in each of the temporally distributed study phases. In other words, they focused on repetitive learning. New materials were presented only at the beginning, and the same material (or related material referring to the same core principle) was restudied in subsequent phases. Spacing versus massing in this context means that restudying the materials is either temporally spaced across several learning sessions or massed in the same session as the initial learning. Clear evidence for the effectiveness of spacing exists only for this specific kind of learning situation (e.g., Cepeda et al., 2006).

However, it is a common misconception, fueled by general recommendations given in study guides (e.g., Putnam et al., 2016), that spacing benefits learning at large. In fact, the question of whether the spacing effect also emerges with *learning materials in which new and consecutive information is presented in the different study phases* has been largely neglected. This approach is typical for educational contexts because it addresses meaningful learning. For example, when a learning unit (e.g., on the ecosystem deep see in biology) extends across several lessons, these lessons could be presented in a massed fashion (e.g., all on one day or as a weekend course) or in a spaced fashion (e.g., spread across several weeks) with lessons in other school subjects between the spaced sessions, which is typical for the schedules in most schools. Another example typical of learning at schools or universities is when learners study two or more complementary texts, that is, multiple texts that are "convergent and require adding pieces of information together" (Primor & Katzir, 2018, p. 4; see also Richter et al., 2020). This approach builds a complex mental representation in contrast to the mere repetition of learning material, where only a certain aspect (e.g., a formula or vocabulary) is encoded and consolidated.

The few studies that implemented spacing with nonrepetitive learning materials revealed contradictory results. Smith and Rothkopf (1984) presented university students with four video-taped statistics lessons (each lasting for 2 hours) either on 1 day or on 4 consecutive days. After 5 days, students were asked to freely recall the topics and symbols covered by the lectures. In addition, students completed a cued recall test, a matching test, and a problem-solving test, all referring to the lectures. Students in the spaced condition outperformed those in the massed condition on the free and cued recall tests, but the effect was not found for the other two learning outcomes. The results suggest that spacing consecutive information can enhance at least some aspects of mathematics learning which refer to factual knowledge and less to procedural knowledge (i.e., problem-solving).

In another study (Vlach & Sandhofer, 2012), 5- to 7-year-olds were presented with four science lessons that addressed the principle of food chains but differed in the biomes involved; thus, the content was not fully repeated. Children who saw the lessons on 4 consecutive days could better generalize the principle to a new biome not previously studied compared to children who received all four lessons on one day.

Randler et al. (2008) presented seventh-graders with four 45 min consecutive biology lessons on the ecological adaptation of the water lily in either a massed fashion (i.e., 180 min in a row) or distributed with one lesson per week. Immediately after the last lesson, learners in the massed-study condition outperformed learners in the spaced-study condition in their knowledge of the covered concepts, whereas no difference between the two conditions was revealed 7 weeks later.

A similar pattern of results was reported by Greving and Richter (2021). In their study, seventh-graders read two consecutive expository texts about biology and physics, respectively, in either one session (i. e., massed) or with a break of one week (Experiment 1) or 15 min (Experiment 2). In both experiments, students in the massed reading condition outperformed students in the spaced reading condition on an immediate test and on a test after 1 week. However, the knowledge decay was smaller in the spaced than in the massed condition, suggesting that the spacing of coherent learning material (i. e., texts) might contribute to a more stable knowledge base that decays more slowly. However, an important finding is that no positive spacing effect occurred in the test after 1 week. In fact, the spaced study of consecutive material is not addressed by most of the theoretical accounts outlined earlier, except for the deficient processing account, suggesting a general benefit of cognitive breaks for learning. In sum, more research is required to examine the stability of this finding and to evaluate whether a spacing effect for coherent, accumulative content exists and whether it depends on further conditions such as the learning schedule, the learning material, or learners' motivation.

Which Role Does Feedback Play for the Spacing Effect?

Another open question concerns the role of *feedback during the study phases* for the spacing effect when a new skill (e. g., solving a certain type of mathematical problem) is practiced with different but similar tasks. In a typical implementation of spacing for learning a skill, a certain skill is introduced initially and then practiced in temporally separated practice phases, necessitating the retrieval of initially taught information (e. g., the mathematical procedure needed for solving the tasks). Given that the benefit of the testing effect, which is based on retrieval during the learning phase, depends on retrieval success (Landauer & Bjork, 1978), the same mechanism might apply to the spacing effect. If learners cannot retrieve the initially acquired information in a subsequent, delayed practice session, they will not profit from any further (spaced or massed) practice if not supplied with further cues. Thus, in line with the study-phase retrieval account, feedback (e. g., the correct solution) or the availability of the initially taught information might be an essential prerequisite for the spacing effect when retrieval between the different study phases is unsuccessful. We can draw this conclusion in analogy to studies showing that practice tests are not effective when retrieval is unsuccessful and no feedback is given (e. g., Agarwal et al., 2008; Greving & Richter, 2018).

We should note on this point that spacing used to acquire a skill (procedural knowledge) is different from spacing used to retain information (declarative knowledge). In spacing experiments involving the retention of declarative information, active retrieval is usually not required because the information is presented again in restudy sessions. An exception is successive relearning, which combines spacing and retrieval practice principles. Successive relearning can be a powerful tool for the long-term acquisition of knowledge in educational contexts (e. g., Butler et al., 2014; Carpenter et al., 2009; Higham et al., 2022; Hopkins et al., 2016; Kapler et al., 2015; Lyle et al., 2020; Rawson et al., 2013)

Which Roles Do Errors and Cueing Marginal Knowledge Play for the Spacing Effect?

Related to the aspect of feedback is the *role of errors* for the spacing effect. As suggested by other research, errors and false responses – particularly errors followed by corrective feedback – can be productive for learning (e. g., Huelser & Metcalfe, 2012; Keith & Frese, 2005; for overviews, see Metcalfe, 2017; Wong & Lim, 2019). Errors can, for example, trigger self-reflection of one's actions (VanLehn, 1999) or elicit cognitive conflicts that learners are motivated to solve (e. g., Kang et al., 2004). Spacing – with especially long ISIs – increases the number of retrieval failures, which in turn can elicit more optimal encoding strategies of the learners, such as investing more time to study (Bahrick & Hall, 2005). Again, note that this proposition only holds for studies in which the to-be-learned information is not presented again, such as in spacing combined with restudying.

On a related note, failing to retrieve previously learned information but being able to recognize this information because it is still stored in memory has been denoted *marginal knowledge* (Bahrick, 2005), which should be distinguished from fully forgetting (i. e., being unable to retrieve or recognize any of the information). Marginal knowledge often fluctuates over time because it is not fully consolidated. The fluctuation is either downward when knowledge is accessible in a first test but not in a subsequent test, or upward when knowledge is inaccessible in a first test but accessible in a subsequent test. One example of marginal knowledge is the "tip of the tongue" phenomenon, when individuals are sure that they know something but cannot retrieve this information (e. g., Brown & McNeill, 1966). Contextual variability can be one factor affecting the accessibility of marginal knowledge (Bahrick & Hall, 1991). For example, memory cues, inherent in multiple-choice tests, may activate access to marginal knowledge. In a recent study (Butler et al., 2020), students first acquired pharmacy concepts and then took part in a pretest about this information. Only 24 % of the initial information was recalled, and 76 % was either forgotten or inaccessible. After 1 week, one group of students worked on multiple-choice tests about the previously acquired information without feedback (experimental group), and another group received no test (control group). After 3 weeks, a final test followed. Of the information not recalled in the pretest, students in the experimental group recalled 42 %, whereas students in the control group recalled only 17 %. Thus, the intermediate multiple-choice test markedly improved the recall of previously unrecallable information, despite receiving only retrieval cues and no feedback. As Bahrick suggested (2000; Bahrick & Hall, 1991), successfully retrieving marginal information can prevent downward fluctuation. This effect is enhanced the longer the interval is between the first acquisition and retrieval. Thus, a combination of spacing and testing can render marginal knowledge accessible. Further research is needed to examine whether the effect is also robust in educational contexts, and whether it applies to coherent material that goes beyond isolated facts.

How Can Spacing Be Promoted in the Context of Students' Self-Regulated Learning?

Students should implement spacing in their self-regulated learning if we assume a beneficial effect of spacing for lasting learning in educational contexts that involve coherent, complex material. When restudying or practicing certain skills, students should start early and use shorter, temporally distributed relearning sessions to prepare for an exam instead of cramming the night before. Unfortunately, many learners tend to adopt the latter strategy (i. e., they procrastinate; e. g., Wäschle et al., 2014). In experimental studies, learners in the spaced condition often completed their practice tasks less frequently than learners in the massed condition, even if the practice schedule was prescribed and students were explicitly prompted to work on the tasks (Barzagar Nazari & Ebersbach, 2018b; Ebersbach & Barzagar Nazari, 2020). Accordingly, learners are often unaware of the benefits of spacing (Pyc & Rawson, 2012) and judge massed learning as at least as effective as massed learning, even though they have experienced the positive effects of spaced learning (Logan et al., 2012). Thus, experiencing the benefits of spacing alone might not promote the application of this strategy in students' self-regulated learning. Students could be additionally provided with an explanatory model for the spacing effect and examine whether this enhances the spacing of their learning activities in self-regulated learning settings.

Does the Spacing Effect Depend on Learners' Prerequisites?

As outlined earlier, exploring interindividual differences in learners on the spacing effect could be informative – a largely neglected aspect. One study (Barzagar Nazari & Ebersbach, 2019) suggests that the spacing effect might be more powerful (or only emerge) for students at a medium performance level who have no fundamental problems working on the practice tasks and who have also not yet achieved mastery. Poor-performing learners might benefit from corrective feedback in the practice phases to perform successfully. Other learner variables might also affect the spacing effect, for example, their prior knowledge. In educational contexts, prior knowledge plays a larger role than in the laboratory, where completely new or even artefactual information must be learned. Another learner characteristic that might interact with the spacing effect is working memory capacity, especially when spacing involves retrieval practice. Learners with a larger working memory capacity might be better able to retrieve previously acquired knowledge and apply it to the practice tasks. In addition, metacognitive skills and knowledge might be an advantage when learners successfully implement multiple-spaced learning sessions in their self-regulated learning (Bahrick, 2000). Finally, related to the preceding issue, students' motivation might contribute to whether spacing is used at all and whether it yields a positive effect or not, especially when spacing is applied in the context of students' self-regulated learning.

Summary

A considerable body of research has demonstrated the positive effects of spacing the total study time across different sessions instead of massing it in one learning session to acquire lasting knowledge. However, despite quite general recommendations of some authors to apply spacing in educational contexts, the available evidence is limited in certain respects. This manuscript aimed to identify some open questions that must be answered first before spacing can be recommended to teachers and learners as an effective learning principle that promotes lasting learning. First, spacing is established as an effective learning technique for repetitive learning, for example, when information is restudied or a cognitive or motor skill is practiced repeatedly with similar or even identical tasks. Evidence for the positive effects of spacing for learning new, nonrepeated content is scarce, and the available studies are inconsistent. Second, most studies were conducted in the laboratory, involving simple, verbatim material that addressed declarative knowledge. Given that learning in the laboratory greatly differs from learning in educational contexts (e.g., the learning content, the role of learners' characteristics, and the learning setting), further research is needed to examine whether the spacing effect also emerges reliably for the acquisition of curriculum-relevant knowledge and skills in schools and universities. Moreover, to better understand the spacing effect, we need a more differentiated view of the operationalization of spacing (e.g., fully-massed vs. less-spaced vs. more-spaced), the content-specificity of the effect (e.g., repetitive vs. related vs. accumulating study material or verbal vs. nonverbal material), and the learning outcome (e.g., declarative vs. procedural knowledge vs. transfer vs. comprehension). Further questions that need to be addressed by future research pertain to the role of feedback and errors for the spacing effect, its interaction with interindividual differences in cognitive and motivational variables, and the motivation of learners to implement spacing in their self-regulated learning.

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