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Review article

Buildup and release from proactive interference – Cognitive and neural mechanisms

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ABSTRACT

Interference from related memories is generally considered one of the major causes of forgetting in human memory. The most prevalent form of interference may be proactive interference (PI), which refers to the finding that memory of more recently studied information can be impaired by the previous study of other information. PI is a fairly persistent effect, but numerous studies have shown that there can also be release from PI. PI buildup and release have primarily been studied using paired-associate learning, the Brown-Peterson task, or multiple-list learning. The review first introduces the three experimental tasks and, for each task, summarizes critical findings on PI buildup and release, from both behavioral and imaging work. Then, an overview is provided of suggested cognitive mechanisms operating on the encoding and retrieval stages as well as of neural correlates of these mechanisms. The results indicate that, in general, both encoding and retrieval processes contribute to PI buildup and release. Finally, empirical gaps in the current work are emphasized and suggestions for future studies are provided.

1. Introduction

In today's society, we almost constantly have to process a plethora of information that is directed at us, be it at work or when we try to stay up-to-date on current political and societal topics. The continuous addition of new information to our long-term memory poses a major challenge for the targeted recall of information relevant to the accomplishment of a current task. Indeed, when two or more memories are related but we want to access only one of them, interference can arise. Suppose you are trying to remember a politician's current stance on a given topic, like tax policy. Even if you tend to follow the news very closely, you may have difficulty with this task if the politician has previously flip-flopped on the issue, and you remember both an interview in which they favored tax increases as well as a statement where they argued in favor of tax breaks. If you cannot clearly distinguish which statement came first and which came last, you will likely experience difficulty at recalling the politician's most recent position on the issue. However, if you are able to separate the two statements on a temporal basis, you may resolve the interference and produce the correct response.

Interference effects like those encountered in our everyday lives directly relate to the two most prominent forms of interference studied in the memory literature: retroactive interference and proactive interference. Retroactive interference was first reported by Müller and his student Pilzecker in their monograph in 1900. Müller and Pilzecker (1900) showed that retention of some originally studied (target) information – for instance, the information that a politician initially voiced support for tax increases – was worse when study of that information was followed by the study of interpolated (nontarget) information – e.g., the information that the same politician later supported tax breaks. Retroactive interference had been widely accepted as the major factor underlying episodic forgetting (e.g., Jenkins and Dallenbach, 1924; Skaggs, 1925), when Underwood (1957) published a seminal paper in which he demonstrated that memory failure is not always due to the detrimental effects of subsequent nontarget learning. Indeed, to stay with our example, correctly remembering that a politician currently favors tax breaks can be complicated when the politician earlier expressed support for tax increases. More generally speaking, forgetting can be caused by the detrimental effects of nontarget information studied *prior* to the study of the target information, i.e., proactive interference [PI]. Since the late 1950s, PI has been extensively studied, with results indicating that PI arises over a wide range of materials and settings and may indeed reflect one of the major causes of forgetting in human memory (for reviews, see Anderson and Neely, 1996; Crowder, 1976).

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Given that the additional learning of nontarget information – be it prior to or subsequent to the study of some target information – can impair the targeted use of our memory in many situations, it would be desirable to have a range of tools available to reduce such interference. Memory research over the past decades has identified such tools. For instance, Ekstrand (1967) provided a classic demonstration that sleep can help to reduce retroactive interference. This researcher showed that the detrimental effects of subsequent learning of (nontarget) material on initially studied (target) material can be reduced when the interval prior to test of the target material was filled with sleep rather than wakefulness. A classic example of PI release comes from Tulving and Watkins (1974), who showed that the detrimental effects of prior nontarget learning can be reduced when the nontarget material is tested prior to study of the subsequently learned target material.

The specific goal of the present review is to focus on PI as a central form of forgetting, and provide an overview of both the classic and more recent findings on (i) buildup of PI and (ii) methods that can enable release from PI. Results from several lines of research have demonstrated PI buildup particularly in three types of memory tasks: in paired-associate learning, the Brown-Peterson task, and multiple-list learning. In paired-associate learning, participants may initially study a first (nontarget) list of stimulus-response word pairs (e.g., *house*-RENT, or A–B) and then a second (target) list of pairs where the same stimulus word is presented as in the first list but a new response word is connected to each stimulus word (e.g., *house*-LEASE, or A–D). On the final test, the 'A' stimulus word is shown as a cue (e.g., *house*-?) and participants are asked to recall the response word of the second (target) list (LEASE, or the 'D' response). Recall of the 'D' response is typically impaired when compared to a control condition in which the 'B' and 'D' responses are linked to different stimulus words (e.g., *earth*-ROUND; *table*-COOK, or A–B, C–D), thus reflecting PI buildup (e.g., Greeno, 1964; Postman and Underwood, 1973). In the Brown-Peterson task, participants study multiple lists of items which, for instance, may all belong to a single semantic category (e.g., SPORTS). After study of each list and a short distractor task, they are tested on the immediately preceding list (e.g., Wickens, 1970, 1973). Recall performance typically declines across lists, reflecting buildup of PI. Finally, in multiple-list learning PI designs, participants may study a target list of unrelated items (e.g., *nose*, *wind*, *mouse*, etc.) and are then tested on it. PI buildup in this task is reflected in the finding that target list recall is typically worse when, prior to study of the target list, additional nontarget lists were studied compared to when subjects engaged in unrelated distractor activities for the same duration of time (e.g., Postman et al., 1968).

For each of the three tasks used to induce PI buildup, multiple ways have been identified by which PI buildup can be released. In paired-associated learning, for instance, PI can be reduced as a result of prior experience with PI (e.g., Wahlheim and Jacoby, 2011) or when participants are reminded of the nontarget material during subsequent study of the target material (Wahlheim and Jacoby, 2013). In the Brown-Peterson task, participants can show a recovery from PI when the target material is dissimilar in content from the previously studied nontarget material (e.g., Gardiner et al., 1972) or when the time interval between study of the nontarget material and the subsequent study of the target material is increased (e.g., Kincaid and Wickens, 1970). Finally, in multiple-list learning, a PI reduction can be achieved by directing participants prior to study of the target material to forget the just studied nontarget material (e.g., Bjork et al., 1968) – for instance, by emphasizing that it would not be relevant for the later memory test – or when there is a change in context between the prior encoding of the nontarget material and the subsequent encoding of the target material (e.g., Sahakyan and Kelley, 2002). Interpolated tests of the nontarget material prior to study of the target material can also release PI (e.g. Szpunar et al., 2008).

Theoretical explanations of PI buildup and release assume that both encoding and retrieval processes can critically contribute to the two types of PI effects. Retrieval processes have been argued to be critically involved in PI buildup because the prior study of nontarget material makes it more difficult at the time of test to focus the memory search on the target information. Regarding PI release, an improved ability to differentiate between the nontarget and target material has been suggested to underlie PI release, although the proposals about the nature of the cognitive processes enabling such enhanced discrimination vary across experimental tasks. For instance, enhanced discrimination may be induced due to a greater reliance on the ability to recollect the target material (Jacoby et al., 2010), the use of more effective retrieval cues (Wixted and Rohrer, 1993), or by making the nontarget material more distinctive, so that on a posthoc basis, it can be easier filtered out from the mental search set (Thomas and McDaniel, 2013).

Encoding processes have also been assumed to contribute to PI buildup and release. Regarding PI buildup, the prior study of nontarget material has been suggested to impair subsequent encoding of the target material, because attentional resources can deteriorate with amount of encoded information and thus impair target encoding (Crowder, 1976; Pastötter et al., 2011). Several processes have been argued to induce PI release at the encoding level, and these processes seem to vary with the single tasks. For instance, the encoding problem may be prevented through a reset process that makes the encoding of the target material again as effective as the encoding of the initially studied nontarget material (e.g., Pastötter et al., 2008); or the encoding problem may be compensated by the use of more effective strategies to encode the target material, relative to the prior encoding of the nontarget material (e.g., Sahakyan and Delaney, 2003). PI release may also result from a mixture of encoding and retrieval processes. This may occur when, during encoding of the target material, individuals are reminded of the nontarget material, which may result in an integrated memory representation – including both the target and the nontarget material as well as information on the order in which the two types of material were provided – and improved recall of the target information (e.g., Wahlheim and Jacoby, 2013).

In this review, we first provide an overview of the three experimental tasks that have traditionally been used to induce PI buildup, before we report for each task the various methods that have been applied to induce PI release. For both PI buildup and each of the single PI release methods we report (a) the basic procedure and main findings, (b) the suggested cognitive mechanisms operating on the encoding and retrieval stages, and (c) the current knowledge on neural processes operating on each of the two stages. A final summary section will discuss results on PI buildup and release methods, emphasize empirical gaps in the current work, and offer suggestions for future studies.

2. PI buildup and release in paired-associate learning

2.1. PI buildup

Paired-associate learning was first introduced in the late 19th century by American philosopher and psychologist Mary Calkins (Calkins, 1894). In many respects, this type of PI-buildup task is representative of the stimulus-response associationist analysis of learning that dominated experimental psychology in the first half of the 20th century. In a typical A–B, A–D paired-associate learning task, participants initially study a first (nontarget) list consisting, for instance, of stimulus-response word pairs (e.g., *house*-RENT, or A–B) and then a second (target) list consisting of additional pairs. In these additional pairs, either the first-list stimulus word is repeated but a new response word is connected to the stimulus word (e.g., *house*-LEASE, or A–D), or both the stimulus word and the response word differ from the first list (e.g., *earth*-ROUND; *table*-COOK, or A–B, C–D). In some studies, a further type of pairs is included in list 2, in which both the stimulus and the response terms are repeated (A–B, A–B). On a later test, the stimulus word is shown and participants are asked to recall the appropriate response word of the second (target) list. Recall of the target response is typically impaired for A–B, A-D pairs, when compared to A–B, C–D (and A–B, A–B) pairs, thus reflecting PI buildup (e.g., Greeno, 1964; Postman and Underwood, 1973; see Fig. 1a and b). Over the years, PI buildup in paired-associate learning has been examined across a wide variety of learning conditions. For instance, PI has been found to increase with higher degree of learning of the initial nontarget list (Atwater, 1953; Underwood, 1949; but see DaPolito, 1966) or increasing length of the retention interval (Dallett (1964), Underwood (1948)). PI buildup in this task has also been demonstrated across many different types of study materials, including syllable-noun pairs (e.g., Postman et al., 1968), noun-noun pairs (e.g., Wahlheim and Jacoby, 2013), odor-picture pairs (Lawless and Engen, 1977), picture-word pairs (Biss et al., 2013), or pairs of colors and color words (e.g., Saufley and Underwood, 1964).

Accounts of PI buildup in paired-associate learning generally attribute the locus of PI buildup to the retrieval stage. McGeoch's (1942) response-competition theory, for instance, assumes that the forgetting arises because, at the time of test, the to-be-recalled target information is blocked by competing information. In the A–B, A–D task, two different responses, 'B' and 'D', are learned together with the same stimulus 'A', and when the stimulus 'A' is later at test presented as a retrieval cue for the target response 'D', the unwanted 'B' response may be retrieved and block retrieval of the target 'D' response. Such competition would lead to worse memory of the 'D' response than in the A–B, C–D control condition, in which the 'D' response is only linked to a single stimulus. Evidence for the view that competition contributes to PI comes from studies showing that recall of the 'D' response decreases as the number of A–B study cycles is increased and increases as the number of A–D study cycles is increased (e.g., Anderson, 1983; Mensink and Raaijmakers, 1988; Postman et al., 1974). Indeed, repeated study practice of A–B pairs should increase the strength of the 'B' response relative to the 'D' response, thus enhance competition from the 'B' response and lead to the observed pronounced forgetting of the 'D' response. Similarly, repeated study practice of A–D pairs should increase the relative strength of the 'D' response, thus lessen competition from the 'B' response and enable the observed recall enhancement for the 'D' response.

Underwood (1945) suggested an alternative PI account which holds that immediately after study of the second list, differentiation of the two lists is high and the target responses are easily accessible. But as the retention interval increases, the apparent recencies of the two lists intersect, making it increasingly difficult to distinguish target from nontarget responses on a temporal basis at the time of test. This list-differentiation view can explain why PI is often not found when the retention test occurs immediately after learning, but is typically present when the retention interval is prolonged (e.g., Koppenaal, 1963). Further support for the view comes from the demonstration that recall of A–D pairs in a typical A–B, A–D task was better when A–B learning trials were being spaced out across four days than when they were massed on a single day (Underwood and Ekstrand, 1967), and from the observation that less PI was observed when the learning of the A–B and A–D pairs was separated by three days (Underwood and Freund, 1968; but see, Hintzman and Waters, 1969). Finally, the finding that retrieval practice of the previously studied A–B pairs prior to study of the A–D pairs can reduce PI (Tulving and Watkins, 1974) is also in line with the list-differentiation view. Indeed, distributed practice of the prior nontarget material, increased temporal separation of the study of the nontarget and target materials, as well as interpolated retrieval practice of the nontarget material prior to study of the target material may all make the A–B items more easily differentiable from the A–D items on a temporal basis. Critically, response competition and list differentiation are not mutually exclusive, and each of them may contribute to PI buildup (for a thorough discussion, see Crowder, 1976).

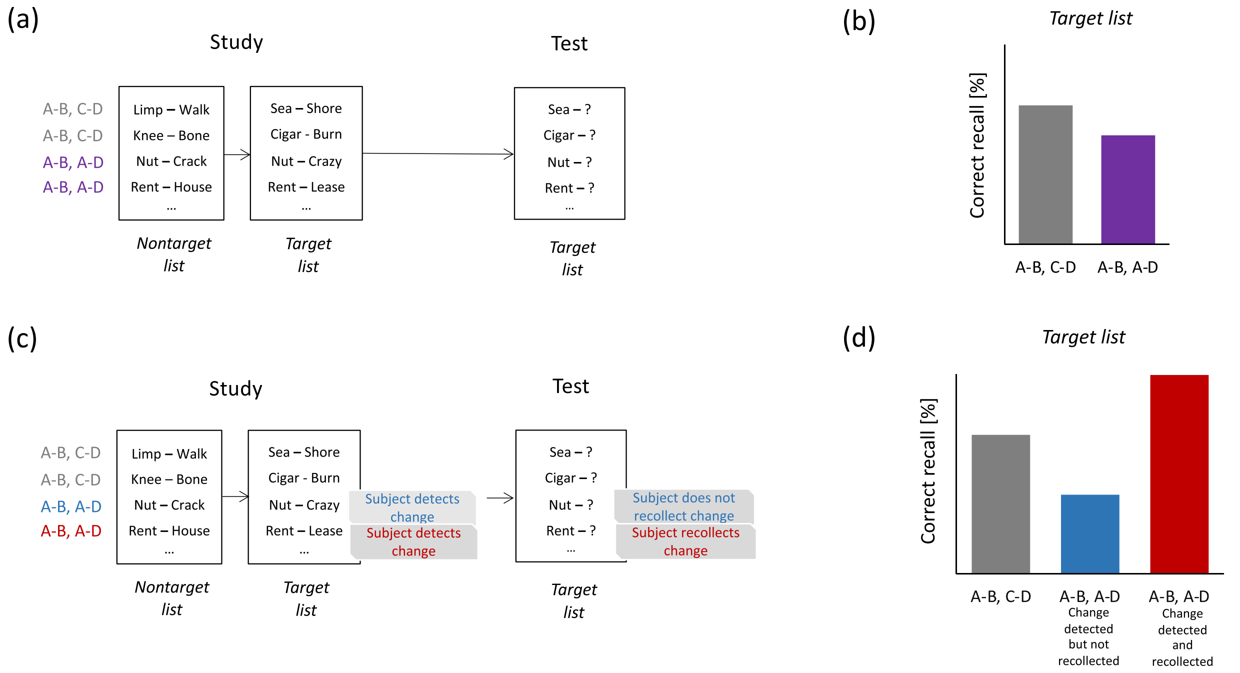

Fig. 1. (a) PI buildup in paired-associate learning: Participants study a target list of stimulus-response pairs that is preceded by a list of other (nontarget) pairs. The target list consists of two types of word pairs: new pairs for which neither the stimulus word nor the response word had appeared in the nontarget list (A–B, C–D); and pairs for which the stimulus word had already appeared in the nontarget list but the response word is new (A–B, A–D). (b) Typical results: Relative to A–B, C–D pairs, recall of the target 'D' response in A–B, A–D pairs is impaired. (c) Proactive facilitation in paired-associate learning as induced by change detection and subsequent change recollection: During study of the target list, participants are asked to indicate pairs for which responses have changed (A–B, A–D) and to recall the nontarget response (change detection). At test, the stimulus word of each target pair is presented and participants are asked to recall the target response. Change recollection is indicated if participants additionally report the appropriate nontarget list response word. **(d)** Typical results: Relative to A–B, C–D pairs, recall of the target 'D' response in A–B, A–D pairs is impaired when changes in responses were detected but not recollected, reflecting PI buildup. In contrast, recall of the target 'D' response is improved when changes in responses were detected and recollected, reflecting proactive facilitation.

2.2. PI release

2.2.1. Experience with PI

While research in the late 1960s (Underwood and Ekstrand, 1967; Underwood and Freund, 1968) thus had already provided a few demonstrations of how PI can be reduced in paired-associate learning, more recent research has found a renewed interest in determining effective PI-release methods in this task. Findings from this research, for instance, suggest that prior experience with PI can reduce its detrimental effect on memory (Jacoby et al., 2010; Wahlheim and Jacoby, 2011). Jacoby et al. (2010) applied a typical A–B, A–D learning task, but after completion of the task, there was a second round of experience with the task in which participants learned new material. The goal was to examine how the first round of experience with PI affected learning and memory in the second round. Results showed that participants were more accurate in the A–B, A–D condition in the second round than the first round as is reflected by the fact that, across rounds, the number of correctly recalled ‘D’ (target) responses increased, and the number of incorrectly recalled ‘B’ (nontarget) responses decreased. At the time of test, participants were also asked to judge their confidence that a given item they recalled had been studied in list 2. These confidence judgments indicated that prior experience with PI improved the resolution of confidence judgments, as was documented by an increased ability to distinguish between the ‘D’ (target) and ‘B’ (nontarget) responses.

There is evidence that experience-based PI reduction may be the result of both enhanced encoding and retrieval. Evidence for adjustments in the retrieval process may be reflected in the improved resolution of confidence judgments in the interference condition that was observed as a result of a prior round of A–B, A–D learning. In particular, participants may have been unable to properly distinguish between the ‘B’ and ‘D’ responses at the time of test in round 1 and this realization may induce the use of a more optimal retrieval strategy in round 2. Concretely, Jacoby et al. (2010) suggested that participants at test may shift away from a fluency heuristic in the first round to a recollection heuristic in the second round. Relying on fluency as a basis for confidence judgments – i.e., on the ease with which a response comes to mind when presented with the cue word (e.g., Jacoby et al., 2005) – would indeed result in a faulty confidence in ‘B’ intrusion errors, because the participant encountered the ‘B’ response during study of list 1. In contrast, a heavier reliance on the ability to actually recollect the presentation of the ‘D’ target item during list-2 learning as a basis for the confidence judgment in the second round should result in more precise confidence ratings, which is exactly what Jacoby et al. observed.

Evidence for enhanced encoding comes from the demonstration that when participants were allowed to self-allocate their study time, they devoted less study time to A–B, C–D pairs in the second round than the first round, but more study time to A–B, A–D pairs in the second round than the first round (Wahlheim and Jacoby, 2011). The finding suggests that participants became aware of the greater difficulty of A–B, A–D pairs in the first round, so they used more time to learn those items in the second round. Specifically, participants may have decided to allocate more study time to a given ‘D’ response in an A–B, A–D pair when they were able to detect a change in responses between the first and second list during presentation of the A–D pair.

2.2.2. Detecting change

Recent research also suggests that PI can be reduced in paired-associate learning when changes between initially studied nontarget information and subsequently studied target information are rare but, when they occur, are detected and recollected at test by the participant (e.g., Jacoby et al., 2015; Wahlheim and Jacoby, 2013). Such change detection and recollection can even reverse PI and thus lead to proactive *facilitation*. A number of studies have recently provided evidence for such a facilitation effect using a variant of paired-associate learning, in which, during encoding of the target list, participants were asked to indicate pairs for which responses had changed (A–B, A–D) and to recall the nontarget response (B). Successful production of the nontarget response was seen as an indication of change detection. At a later cued-recall test, the stimulus word of each target pair was presented and participants were asked to recall the target response. In addition, participants were instructed that, if another word came to mind prior to or simultaneously with a word that they produced as being the target response, they were to report the word that came to mind. If subjects reported the nontarget response, this was treated as change recollection (see Fig. 1c).

Results showed that typical PI occurred when changes in responses were not detected during target encoding or were detected but not recollected at test. In contrast, proactive facilitation arose when changes in responses were both detected and recollected at test by the participant (see Fig. 1d). Performance on A–B, A–D pairs can thus reflect a mixture of facilitation and interference effects. Several further studies have demonstrated beneficial effects of detecting and recollecting change across a variety of materials, like when using semantically related word pairs (Jacoby et al., 2013), positions on controversial issues held by fictional political candidates (Putnam et al., 2014), everyday actions performed by an actor (Wahlheim and Zacks, 2019), or with actual fake news misinformation and subsequent corrections (Wahlheim et al., 2020).

Proactive facilitation effects in the A–B, A–D task have been attributed to recursive remindings. The suggestion is that when a change in responses is detected during learning of the target list (i.e., when reminding occurs), retrieval of the nontarget response may facilitate the formation of an integrated memory trace that embeds the nontarget response into the representation of the target response along with information about the study order in which the two responses occurred (Hintzman, 2004; Wahlheim and Jacoby, 2013). Recollection of the recursive reminding at test may then induce proactive facilitation because integrated memory traces containing both responses and their relative study order may provide additional retrieval cues, and may thus facilitate recall of the target response. Evidence for the recursive-remindings view comes from work showing that detection and recollection of change enhances list discrimination at test by increasing the probability that participants correctly attribute a pair as having been presented with the target list (Jacoby et al., 2013). Importantly, the degree to which reminding occurs can be brought under task control, as conditions which encourage participants to look back over time during target encoding (i.e., by instructing them to detect changes with respect to the preceding nontarget list) can lead to enhanced change detection and recollection and can thus promote proactive facilitation (Jacoby et al., 2015). Attention during A–D encoding can also influence reminding. Consistently, Wahlheim and Garlitch (2020) reported a positive relationship between participants’ self-reported attention level during the encoding of A–D pairs and later change recollection. Furthermore, retrieval practice can foster reminding, with Wahlheim (2015) showing that change recollection improves when, prior to study of the A–D list, there is interpolated retrieval practice of the previously studied A–B list.

2.3. Neural correlates

Applying PET and fMRI, several studies investigated the neural processes underlying PI in paired-associate learning. PET has thus far been used during encoding, whereas fMRI has been used during both encoding and at test. In an early imaging study, participants underwent PET while they engaged in a typical paired-associate learning task (Dolan and Fletcher, 1997). Increased activity in the lateral prefrontal cortex (PFC) – including both ventrolateral and dorsolateral PFC – was found while participants encoded the A–D pairs, relative to when they encoded completely new C–D pairs. The authors argued that the lateral PFC may be engaged when associative semantic processing is required in establishing a new (A–D) link between a stimulus and a response in the context of an already existing (A–B) link.

Applying fMRI during encoding, Henson et al. (2002) extended upon this finding by showing that activation in the lateral PFC decreased with additional presentations of the A–D pair, suggesting that activity is reduced as the association between the ‘A’ stimulus and the ‘D’ response is strengthened and less PI is experienced. Applying fMRI at the later test, Henson et al. (2002) were further able to demonstrate that lateral PFC showed increased activity when participants had to retrieve A–D pairs after prior A–B encoding. Because left ventrolateral PFC has been found to show increased activity as the number of response words that are linked with a common stimulus word is increased (e.g., Sohn et al., 2005), activity in this region may reflect the increased difficulty of selecting a target response in the presence of interference from other responses.

Regarding PI release in paired-associate learning, no prior study thus far has directly examined the neural underpinnings of how prior experience with PI can induce PI release. However, a number of prior fMRI studies using an A–B, A–D design have examined neural correlates of reminding during A–D learning. The studies thus measured neural activity during encoding, but not at test. In one study, Kuhl et al. (2010) sought to determine how neural mechanisms engaged during the encoding of A–D pairs relate to subsequent memory for initially encoded A–B pairs. These researchers employed a retroactive-interference variant of the A–B, A–D task in which study of the A–B pair was either followed by an A–D pair or not. Behavioral results showed that the ‘B’ responses were recalled more poorly on a later test when they were followed by an A–D pair, which reflects typical retroactive interference. Neurally, it was found that greater activation in the posterior hippocampus extending into parahippocampal cortex during the encoding of the A–D pairs was associated with improved final recall of the ‘B’ responses. In addition, it was found that across individual subjects, greater activation in these areas predicted improved final recall of ‘B’ responses. The findings are consistent with computational theories of hippocampal function (McClelland et al., 1995), suggesting that A–B pairs can get reactivated during A–D encoding, thereby promoting A–B retention.

More recently, Richter et al. (2016) conducted an fMRI experiment in which they provided instructions during A–D learning that either biased subjects’ processing toward encoding of the A–D pair, retrieval of the prior A–B pair, or integration of both pairs. Using multivariate pattern analysis, the researchers demonstrated that it was possible to dissociate the integration state from the encoding and retrieval states. Critically, they showed that, for a new sample of subjects whose processing states were not biased by encoding instructions, the decoding algorithm was able to successfully predict performance on an integration test – a test which assessed the ability to correctly identify the ‘B’ response when presented with the ‘D’ response. Both the hippocampus and medial PFC were found to distinctly index subjects’ mnemonic processing states, with medial PFC being critically involved in reactivation of older memories in service of integration. Following up on this research, Chanales et al. (2019) again applied the decoding algorithm derived from the Richter et al. (2016) sample to show that integration of both the ‘B’ and ‘D’ responses during A–D encoding – but not mere reactivation of the ‘B’ response during A–D encoding – is required to reduce PI.

A very recent fMRI study by Stawarczyk et al. (2020) directly examined the role of neural reactivation of the ‘B’ response during the encoding of the ‘D’ response. In this study, participants were shown a first movie depicting a number of activities in a day of the protagonist’s life, before they viewed a second movie with the same events but with some of the scenes ending in a different way (A–B, A–D pairs). Crucially, before watching the last part of each scene of the second movie, the movie stopped, and subjects were asked to mentally replay how the scene ended previously. Three days later, subjects returned to the lab to engage in an unscanned cued recall test of the ‘D’ responses (i.e., the scene endings of the second movie). A key finding of this study was that stronger reactivation of the episode-specific neural activity pattern in medial temporal and the posteromedial brain areas during the mental replay phases was related to better change detection and recollection. This observation indicates that such reinstatement is related to the encoding of novel, unexpected event features. The researchers proposed, as one possibility, that reinstatement of a ‘B’ response may lead to predictions, which in turn trigger a prediction error signal when events change. The error signal may then initiate integration of the ‘B’ and ‘D’ responses.

2.4. Interim summary

The findings from behavioral work suggest that PI buildup can occur in paired-associate learning because, at the time of test, responses from the initially studied nontarget list compete with the responses from the subsequently studied target list. Additionally, the nontarget and target lists may become more difficult to differentiate, particularly after longer retention interval. The response-competition view is supported by behavioral work systematically manipulating the strength of the nontarget and target materials, whereas behavioral support for the list-differentiation view comes from studies demonstrating increased PI when the retention interval is prolonged. Behavioral work on PI release suggests that prior experience with PI as well as the detection of change during encoding of target information (together with the recollection of this change at test) can induce a recovery from PI or even proactive facilitation. Regarding imaging work on PI buildup, both the response-competition and list-differentiation views are in line with PET and fMRI studies showing that prior nontarget learning leads to increased activity in the lateral PFC, a brain region that has been suggested to be involved when a selection among competing informations is required during demanding retrieval tasks. Regarding imaging work on PI release, it has been shown that the hippocampus and medial PFC may constitute neural substrates of reminding and memory integration, at least in the context of a retroactive interference task. In addition, there is evidence from fMRI work using pattern classifiers that integration of the target material with the prior nontarget material is a precondition to induce PI reduction.

3. PI buildup and release in the Brown-Peterson task

3.1. PI buildup

A second important class of PI tasks is the Brown-Peterson task, which was introduced independently in the late 1950s by Brown (1958) and Peterson and Peterson (1959). In the Brown-Peterson task, participants study multiple lists of items that may consist of strings of letters, words, or numbers. After study of each list and a short distractor task, participants are tested on the immediately preceding list (e.g., Wickens, 1970, 1973). Recall performance typically declines across lists, reflecting buildup of PI (see Fig. 2a and b). Like paired-associate learning, the Brown-Peterson task has been investigated applying various learning and test conditions. For instance, PI has been found to increase with the length of the retention interval, although list-1 forgetting was often comparable between shorter and longer retention interval (Conrad, 1967; Turvey et al., 1970). Furthermore, PI buildup has been found to decrease with the number of presentation cycles of the target list (Fuchs and Melton, 1974) and has not only been observed for free-recall tests, but also recognition tests, like multiple-choice procedures (Gorfein and Jacobson, 1972) or yes-no decision tasks (Gorfein and Jacobson, 1973). PI buildup in the Brown-Peterson task has also been demonstrated over a wide variety of study materials, like prose texts (Blumenthal and Robbins, 1977), pictures (Ellis and Woolridge, 1985), or environmental sounds (Rowe and Rowe, 1976).

Over the years, both encoding and retrieval explanations of PI buildup in the Brown-Peterson task have been suggested. The most prominent retrieval account is temporal discrimination theory. The theory resembles Underwood’s (1945) list differentiation account of PI buildup in paired-associate learning (see preceding section) in assuming that PI accrues due to a failure to distinguish items from the most recent

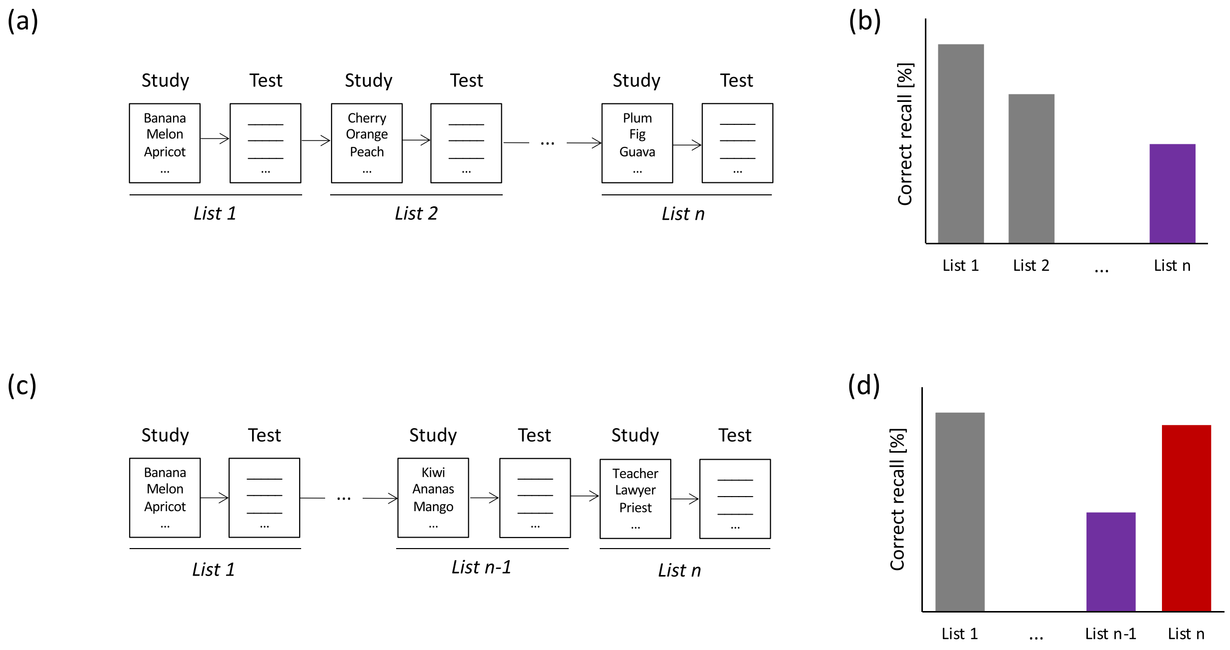

Fig. 2. (a) PI buildup in the Brown-Peterson task. Participants study a target list of items that is preceded by several lists of items, with each list being tested after its initial study. All study items typically belong to a common semantic category, like FRUITS. (b) Typical results: Recall of the target list is worse than recall of the previously learned lists. (c) PI release in the Brown-Peterson task: PI can be reduced in this task by switching the content of the last studied target list, for instance, from FRUITS to PROFESSIONS. (d) Typical results: Recall of the target list (list n) again increases relative to the immediately preceding list (list *n*-1) when there is a switch in content.

target list from items that appeared on the earlier lists. The particular proposal is that, as the number of preceding lists increases, participants may not be able to focus their memory search on the target list, but rather include items from the earlier lists into their mental search set, thus impairing target list recall (Baddeley, 1990; Crowder, 1976). Evidence for the account, for instance, comes from a study demonstrating that when a target list of words was tested in a typical Brown-Peterson task, mean response latency - which measures the speed with which the single study items are recalled at test – increased with the number of previously studied lists (Wixted and Rohrer, 1993). Because mean response latency has been shown to index the size of the mental search set during retrieval (e.g., McGill, 1963), the finding indicates that memory search indeed becomes less focused after the prior study of additional material.

PI buildup has also been attributed to the encoding stage, suggesting that attentional resources may deteriorate and memory load increase from the encoding of the earlier lists to the encoding of the final (target) list (Crowder, 1976). Early support for the account was found in a study which demonstrated that pupillary size, which is regarded as an index of attention (Kahneman and Beatty, 1966), can decrease across successive study lists, suggesting an increase in inattention with amount of encoded material (Engle, 1975). Kane and Engle (2000) provided further evidence for a critical role of attentional resources in PI buildup, demonstrating that when individuals with high working-memory capacity (WMC) performed a secondary task during the encoding of the single lists in a Brown-Peterson task, they exhibited increased PI buildup relative to high-WMC individuals tested in the absence of a secondary task. This suggests that, at least for high-WMC individuals, encoding processes demand attentional resources when other lists were studied previously. In contrast, for low-WMC individuals, the level of PI buildup was similar in the presence versus absence of a secondary task, but was already very pronounced in the absence of the task. Low-WMC individuals may therefore be unable to recruit attentional resources even in the absence of the distraction, and this inability may be critical for their susceptibility to PI.

3.2. *PI release*

3.2.1. *Content switch*

A few years after its introduction, a prominent modification of the original Brown-Peterson task was developed to demonstrate that a release from PI can be achieved when certain aspects of the study material are changed (e.g., Gardiner et al., 1972; Wickens, 1970, 1973; Wickens et al., 1963). Gardiner et al. (1972), for instance, asked their subjects to study four lists of words, but while lists 1–3 all consisted of exemplars from a given category like FRUITS, all list-4 (target) words came from a different category like PROFESSIONS (see Fig. 2c). Results showed that the number of correctly recalled items decreased from list 1 to list 3, thus reflecting typical PI buildup, but again increased from list 3 to list 4, reflecting a recovery from PI (see Fig. 2d). As may be expected, the magnitude of the PI release depends on the level of disparity between the material presented with the earlier lists and the final list, with greater PI release occurring when there is a switch from FRUIT words to PROFESSION words rather than from FRUIT words to VEGETABLE words (Wickens et al., 1976). Furthermore, changes in content language and content modality (i.e., switching from visual to oral presentation) can also induce reliable PI release (Wickens, 1970).

The recovery from PI that a content switch can induce in the Brown-Peterson task has primarily been attributed to retrieval processes. One prominent suggestion is that a content switch enables the use of a more effective retrieval cue at test which makes it easier to exclude the prior lists from memory search, and thus increases the probability of recalling target responses. For instance, Gardiner et al. (1972), who showed that PI release only occurs when a content switch is made explicit to the subjects, argued that participants that were informed about the switch may have used it as a list-specific cue that was helpful at focusing the memory search to only the target items. Wixted and Rohrer (1993) reported more direct evidence in favor of this hypothesis, by showing that providing a subcategory name after study of the target material not only increased recall totals but also reduced response latencies. Because response latencies constitute a reliable index of the breadth of the memory search (see above), these findings support the view that a content switch can enable a more focused memory search – at least, as long as the content switch is made explicit to the subjects.

Results from prior work indicate that a content switch does not improve encoding of the target material. Indeed, while Engle (1975) found a decrease in both recall totals and pupil size in a Brown-Peterson task when PI was built up across lists (see above), there was only an increase in recall totals but no increase in pupil size when there was a switch to a new semantic category. This finding suggests that while attentional resources seem to decrease during the encoding of the initial lists, a content switch may not necessarily help participants to regain attentional control.

3.2.2. Lag between study lists

PI release in the Brown-Peterson task can not only be achieved by content change, but also by increasing the lag between study of the earlier lists and study of the last list. Kincaid and Wickens (1970) had subjects study four lists with each list consisting only of a single consonant trigram (e.g., NCS). No time was interposed between the study of each of the first three lists, but the lag prior to presentation of the fourth list was varied from 0 s to 120 s. Results demonstrated a considerable PI-release effect after 45 s, with a slight additional recovery effect after 120 s. Although studies manipulating the interval between study of the two last lists in the sequence generally found a reliable PI reduction, a complete elimination of PI has typically not been observed (Hopkins et al., 1973; Peterson and Gentile, 1965).

Early accounts of this release effect argued that the prior material simply decays from short-term memory over time and, as a result, there should be less PI from the earlier lists when the target list is studied after a prolonged lag. However, the finding that recall of list-1 items in a Brown-Peterson task does not decrease with increasing lag between study and test of the list (see above Turvey et al., 1970) is clearly inconsistent with the decay view. An alternative encoding-retrieval explanation proposed by Gorfein (1987) may provide a better explanation of why prolonged lag releases PI. Following Estes' (1955) stimulus-sampling theory, Gorfein assumed that prolonged lag leads to stronger variation in the contextual elements that are encoded with the items of the initial lists versus the items of the final target list. As a result, the initial lists and the target list are associated with more distinct contextual cues, which, at the time of test, may allow for a more focused memory search for the target items. While the existing findings on the role of lag for PI release are consistent with this view, we still await a more direct evaluation of the account.

3.3. Neural correlates

To our knowledge, no imaging studies thus far have directly examined the neural underpinnings of how either a change in content or a prolonged lag prior to study of the target list can induce a PI release in the Brown-Peterson task. Rather, a couple of studies using fMRI have applied a modification of the Brown-Peterson task to analyze neural correlates of PI at the time of test (Badre and Wagner, 2005; D'Esposito et al., 1999; Jonides et al., 1998; Mecklinger et al., 2003; Nelson et al., 2003).

In this variant of the task, participants study several lists of items that may, for instance, consist of several consonants (e.g., *f*, *g*, *s*, *m*), as is typical in a Brown-Peterson task. However, different from the usual task, the target list is tested by presenting probe letters that either require a positive response because they match one of the letters of the target list (e.g., *g*; positive probe), or a negative response because they do not match any target letter (e.g., *l*; negative probe). Critically, there are two types of negative probes: recent-negative probes that match an item from the immediately preceding list (list *n*-1) and nonrecent-negative probes that do not match any preceding or target item. The assumption is that while correctly providing a 'no' response to a recent-negative probe would require interference resolution due to the familiarity of recent-negative probes, a correct response to a nonrecent-negative probe would minimize demands on interference resolution. Behaviorally, PI buildup is typically reflected in increased response times to recent-negative probes compared to nonrecent-negative probes (e.g., Badre and Wagner, 2005; D'Esposito et al., 1999; Jonides et al., 1998). Neurally, several fMRI studies have demonstrated that during presentation of the probe, there is typically greater activation in the ventrolateral PFC for recent-negative than nonrecent-negative probes (e.g., D'Esposito et al., 1999; Postle and Brush, 2004). In particular, across subjects, the magnitude of the behavioral PI effect (i.e., the difference in reaction time between recent-negative and nonrecent-negative probes) shows a positive correlation with the magnitude of differential activation in the ventrolateral PFC (e.g., Badre and Wagner, 2005). Both findings suggest a PFC-mediated mechanism that is sensitive to PI.

Regarding the nature of this mechanism, Badre and Wagner (2005), Badre and Wagner (2007) argued that the presentation of a recent-negative probe may require a postretrieval monitoring process that enables participants to arrive at the correct source attribution for why the negative probe seems familiar. This perspective suggests that recent-positive probes, i.e., items that occurred in list n and the (immediately preceding) list *n*-1, should induce competition and increase the demands for a post-retrieval selection process relative to nonrecent-positive probes, i.e., probes that were present in list n only. In particular, while the presence of the probe in list n yields some advantage for the relevant contextual details, the additional retrieval of contextual elements from list *n*-1 should induce competition. The account therefore predicts that recent-positive probes should be associated with increased ventrolateral PFC activation relative to nonrecent-positive probes. Applying fMRI, Badre and Wagner (2005) indeed found a more pronounced activation in the ventrolateral PFC for recent-positive compared to nonrecent-positive probes, which parallels the finding seen in the recent-negative versus nonrecent-negative contrast mentioned above. Overall, the finding of an increased ventrolateral PFC activation during presentation of both recent-negative and recent-positive probes, relative to non-recent probes, aligns with the view that this region is involved with post-retrieval selection processes that reduce interference between simultaneously active contextual elements.

3.4. Interim summary

The findings from behavioral work suggest that, in the Brown-Peterson task, the initial study of item lists can impair both encoding and retrieval of the subsequently studied target material. Regarding retrieval factors, behavioral studies applying response latency analysis at test suggest that PI buildup can result because participants are less well able to focus their memory search on the target items when other material has previously been learned. Regarding encoding factors, behavioral work analyzing pupillary dilation and the role of secondary task during encoding of the single lists indicate that participants' attentional resources decrease from the encoding of the initial lists to the encoding of the final list. PI release in the Brown-Peterson task can be achieved, for instance, when there is a switch in content between the initial material and the subsequently studied target material or when the lag prior to study of the target material is increased. Thus far, behavioral work examining pupil dilation indicates that a switch in content does not reinvigorate attentional resources, but may rather help participants to refocus their memory search on the relevant target items. Behavioral studies on the processes underlying the effects of increased lag are scarce, but they rule out a decay explanation of PI release. Using a recognition version of the Brown-Peterson task, several fMRI studies found PI to be linked to greater activation in the ventrolateral PFC at test, which might indicate that greater postretrieval monitoring occurs in the presence than absence of PI.

4. PI buildup and release in multiple-list learning

4.1. PI buildup

The third prominent task used to study PI is multiple-list learning. PI buildup in this task is typically examined by having participants study a target list – consisting, for instance, of unrelated nouns (e.g., *nose*, *wind*, *mouse*, etc.) – which is either preceded by the study of additional nontarget lists that consist of the same type of study material (e.g., unrelated nouns), or is preceded by unrelated distractor activities for the same duration of time (e.g., simple arithmetic tasks; see Fig. 3a). PI buildup in this task is reflected in the finding that target recall in a later retention test is usually worse in the presence than absence of prior nontarget learning (e.g., Postman et al., 1968; see Fig. 3b). To our knowledge, PI buildup in multiple-list learning thus far has mostly been demonstrated using words as study material.

Like for the Brown-Peterson task, temporal discrimination theory has been suggested as a retrieval account of PI buildup in multiple-list learning. The assumption is that, in the presence of prior learning of nontarget material, participants are not able to focus their memory search on the target list at the time of test, but rather include items from the prior nontarget list(s) into their mental search set, which results in impaired recall of the target items. Consistent with this view, it was shown that, in the presence of prior encoding of nontarget lists, recall totals decreased when the target items were tested and, critically, mean response latencies increased, thus suggesting an enlarged mental search-set size (Bäuml and Kliegl, 2013). Unsworth et al. (2013) extended the finding by showing that prior encoding of nontarget material is not only associated with increased response latencies, but also with a higher number of prior-list intrusions.

Similar to the Brown-Peterson task, PI buildup in multiple-list designs has also been attributed to the encoding stage, suggesting that attentional resources may decrease and memory load increase from the initial encoding of the nontarget list(s) to the final encoding of the target list (Pastötter et al., 2011). Applying EEG, Pastötter et al. (2011) tested this account in more detail (see below). But there is also behavioral evidence for this view coming from a study in which a multiple-list learning task was applied and participants were warned prior to study of the target list that the target list would be later tested. Participants' later recall of the list was improved, relative to when there was no such warning, indicating that the warning helped participants to regain attentional resources (Weinstein et al., 2014). All in all, the results provide evidence that both encoding and retrieval processes can contribute to PI buildup (see also Kliegl et al., 2015).

4.2. PI release

4.2.1. Directed forgetting

Directed forgetting is probably the most extensively studied PI-release tool in the context of multiple-list learning. In the late 1960s, Bjork and colleagues discovered that a cue to forget previously learned (nontarget) material can provide a very powerful means of reducing PI on subsequently learned target material (Bjork et al., 1968). The PI-reducing effects of a forget cue are often examined with a variant of the multiple-list learning design called the list-method directed forgetting task. In this task, participants study two lists consisting, for instance, of unrelated nouns (e.g., *tree*, *iron*, *nose*). They first study a nontarget list (list 1) and then a subsequent target list (list 2) and, after study of the nontarget list, are either asked to keep remembering the just presented list (remember condition) or to forget the list altogether (forget condition). The target list is always to-be-remembered (see Fig. 3a). Sometimes, a single-list baseline condition is included, in which no nontarget list is presented at all but participants instead engage in unrelated distractor activities. At test, participants' memory for both lists is tested irrespective of original cuing.

The typical finding with this task is that, relative to the remember condition, recall of the to-be-forgotten nontarget material (list-1) is impaired and, critically, recall of the to-be-remembered target material (list-2) is improved in the forget condition – suggesting a PI reduction (see Fig. 3b). Oftentimes, target recall is even as high in the forget condition as it is in the single-list control condition, indicating a complete PI elimination (e.g., Bäuml and Kliegl, 2013; Bjork and Bjork, 1996). The effectiveness of providing a forget cue as a means to deal with PI has been demonstrated across a wide variety of study materials, like verbal (e.g., Geiselman et al., 1983), visual (Basden and Basden, 1996), and autobiographical material (e.g., Barnier et al., 2007).

Both encoding and retrieval mechanisms have been argued to underlie PI release in response to a forget cue. Regarding retrieval mechanisms, the observed release from PI has typically been explained by an improved discrimination between the nontarget and target lists, caused

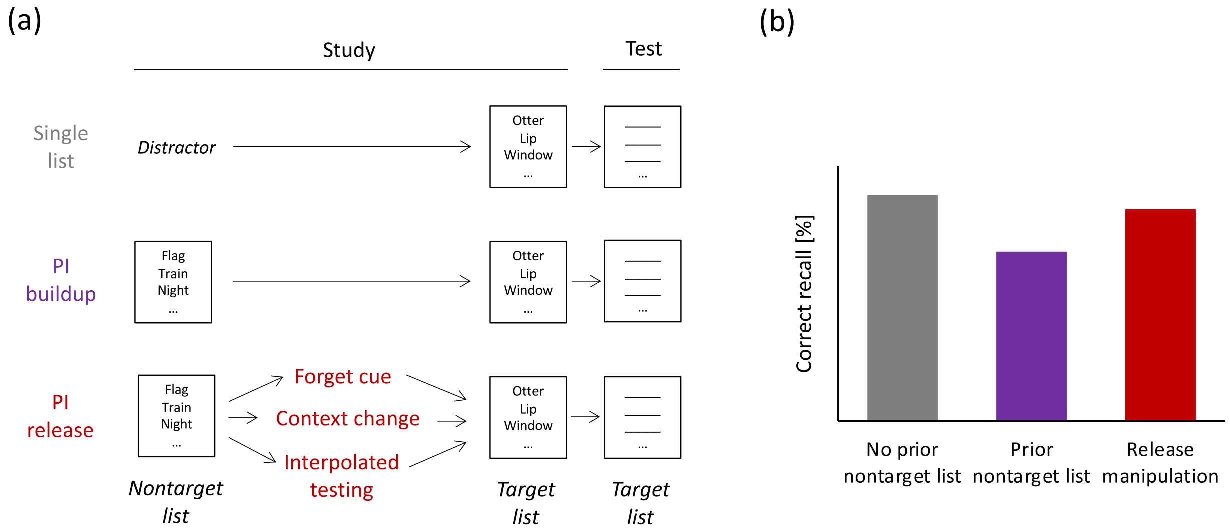

Fig. 3. (a) PI buildup and release in multiple-list learning. PI buildup: Participants study a list of target items that is either preceded by unrelated distractor activity (single-list condition) or the study of one or several additional (nontarget) lists (PI-buildup condition). PI release: Participants study one or several nontarget lists first and a target list second. Before study of the target list, a cue to forget the previous list(s) is provided, a context change is induced, or the previous list(s) is/are tested. (b) Typical results: Target list recall is impaired in the PI buildup condition relative to the single-list condition, but is enhanced in the PI-release condition relative to the PI-buildup condition.

either through processes of contextual unbinding (Geiselman et al., 1983) or contextual drift (Sahakyan and Kelley, 2002). According to the unbinding view, participants in response to the forget cue engage in active inhibitory processes that reduce access to the nontarget list's study context; according to the noninhibitory contextual drift view, the forget cue induces a change in participants' mental context, with the resulting contextual mismatch between study and test contexts causing forgetting of the nontarget items. Following these views, a more focused memory search for the target information should arise and retrieval of the target list be improved, which is consistent with the finding that the forget cue reduces response latencies for the target items, and thus reduces the size of the mental search set at test (Bäuml and Kliegl, 2013). In the same study, latencies in the forget condition were even found to be similar to a single-list condition, suggesting that the forget cue enables a memory search that can be as focused as in the absence of any nontarget encoding.

At the encoding stage, an encoding reset as well as a change in encoding strategy have been suggested to underlie PI release. The reset-of-encoding account assumes that while the prior learning of nontarget material may increase memory load and inattention and thus impair the encoding of the later target list (see above), the forget cue may largely abolish memory load and inattention, thereby resetting the encoding process and making the encoding of early target items as effective as the encoding of early nontarget items (Pastötter and Bäuml, 2010). Indeed, such reset may be expected to be most effective for the early target items, when attention may just have been refreshed, and increasingly less effective for the middle and late target items, when attention may again suffer from the prior encoding of the early (and middle) target items. A number of studies have provided support for this prediction (Pastötter and Bäuml, 2010; Pastötter et al., 2012). In contrast, the strategy-change account proposes that the forget cue can lead participants to adopt a superior encoding strategy for their subsequent learning of the target material (Sahakyan and Delaney, 2003). In support of this view, Sahakyan and Delaney (2003) reported that when participants were not free to choose an encoding strategy but rather were instructed to encode both lists using the same (either shallow or deep) study strategy, they showed no PI-reducing effect of the forget cue at all, suggesting that PI release in response to a forget cue requires a change in strategy between nontarget and target encoding.

4.2.2. Induced context change

In the same year that Bjork et al. (1968) published their seminal work on PI release in response to a forget cue, Dallett and Wilcox (1968) first demonstrated the PI reducing effects of an environmental context change. In this study, subjects learned a target list of unrelated items (list 2) in a distinct physical environment (e.g., a conventional memory lab), and previously learned an additional nontarget list in either the same or a different physical environment (e.g., in a special box with flashing red and green lights; see Fig. 3a). Results showed that target recall was superior when the lists were studied in distinct physical environments than when they were studied in the same environment, suggesting that context change interpolated between study of two lists can reduce PI (see also Eckert et al., 1984; Smith et al., 1978; see Fig. 3b). Evidence from multiple-list learning further suggests that target recall can be improved when the initial nontarget lists and the subsequent target list are all studied in distinct environmental settings each, rather than when all the lists are studied in a common, single environment (e.g., Smith, 1979, 1982).

More recent studies have shown that not only external context change, but also mental (or internal) context change can reduce PI. Sahakyan and Kelley (2002), for instance, asked subjects to study two lists of items and, between study of the two lists, were either asked to engage in a mental imagination task that had subjects either describe their childhood home or what they would do if they were invisible (context-change condition), or to simply wait for an equivalent time until (no-context-change condition). Imagination tasks are similar in content to daydreams which are known to mentally transport people to another place or time (Delaney et al., 2010). The typical finding with this task is that target recall is better in the context-change than the no-context-change condition, suggesting release from PI. Interestingly, mental context change may induce incomplete PI release only, as target recall after induced context change was found to be inferior to target recall in a single-list baseline condition, e.g., when there was no prior study of nontarget items (Bäuml and Kliegl, 2013). To our knowledge, the PI-reducing effect of induced context change has, thus far, been examined using verbal material only.

Both encoding and retrieval mechanisms have been suggested to mediate the effects of induced context change. The most prevalent retrieval explanation is based on the assumption of a context drift mechanism (Sahakyan and Kelley, 2002; Smith and Vela, 2001). This account assumes that, during presentation of the nontarget and target lists, participants store not only information about the target and nontarget items themselves but also about the temporal context in which the material is encountered (Howard and Kahana, 2002; Raaijmakers and Shiffrin, 1981). While typically context drifts slowly over time (Bower, 1972; Estes, 1955) – and thus also drifts slowly between study of a prior nontarget list and study of a subsequent target list –, engaging in an interlist context change may accelerate the contextual drift, and associate the newly learned target list with a more distinct context. This should enable a better discrimination of the target list from the nontarget list at test and a more focused memory search of the target items. Evidence for this view, for instance, comes from prior work analyzing participants' response latencies at test. This work showed that when study of the initial nontarget list was followed by an imagination task, response latencies for the subsequently studied target list were reduced relative to a no-context-change condition, suggesting a reduced mental search set size and more focused retrieval of the target items at test (Bäuml and Kliegl, 2013).

The PI-reducing effect of an induced context change has also been attributed to an improved encoding strategy during study of the target list. Consistent with this view, Sahakyan and Delaney (2003) demonstrated that a change in mental context can induce a PI reduction when subjects are free to choose their own encoding strategies, whereas no PI-reducing effect may arise when subjects are asked to use the same study strategy when encoding the two lists of items. This suggests that PI reduction in context-change tasks may increase when participants switch to a superior encoding strategy while learning the target list items. No behavioral study has examined thus far whether induced context change can also cause a reset of the encoding process, and thus make the encoding of early list-2 (target) items as effective as the encoding of early list-1 (nontarget) items.

4.2.3. Interpolated testing

A further PI release method that has typically been examined in multiple-list learning and that has more recently gained considerable attention in the memory literature is interpolated testing. In a typical experiment, participants may study, for instance, five lists consisting of unrelated nouns in anticipation of a final cumulative recall test, in which subjects are asked to recall all previously studied items. After study of each of the nontarget lists (lists 1–4), participants either engage in unrelated distractor tasks (i.e., maths), immediately restudy each list, or immediately recall the list. All participants are instantly tested on the last studied target list (list 5; e.g., Szpunar et al., 2008; see also Darley and Murdock, 1971). Results show that interpolated testing leads to higher recall for the target list than interpolated distractor tasks or interpolated restudy and can even induce a complete PI release (Pastötter et al., 2011; Szpunar et al., 2008; see Fig. 3b). The same pattern of results arises on the delayed final cumulative recall test. The PI-reducing effect of interpolated testing has been observed over a wide variety of study materials, including lists of related and unrelated items (Szpunar et al., 2008), complex text material (Wissman et al., 2011), faces and names (Weinstein et al., 2011), and videos (Szpunar et al., 2013).

PI-release effects as a result of interpolated testing have been attributed to both encoding and retrieval mechanisms. Retrieval explanations assume that interpolated testing enhances the discrimination between the nontarget and target material due to either contextual drift or postretrieval monitoring. According to the contextual drift view, interspersed retrieval activities alter participants' mental context, thereby enhancing list segregation and enabling the use of list-specific retrieval cues at test (Divis and Benjamin, 2014; Pastötter et al., 2011). According to the postretrieval monitoring view, interpolated retrieval of the initially studied nontarget information may not decrease the probability that, at test, nontarget items are included into the mental search set, but may allow to edit out the nontarget items via a late-correction process (e.g., Hunt et al., 2011; Jacoby et al., 1999; Pierce et al., 2017; Thomas and McDaniel, 2013). A couple of findings are consistent with both views, like, for instance, the observation that interpolated testing reduces the number of intrusions from the previously studied nontarget lists when the target list is tested (e.g., Pastötter et al., 2011; Szpunar et al., 2008). Other results are more compatible with the contextual drift than the postretrieval monitoring view. For instance, interpolated testing has been found to reduce response latencies of the target items at test, thus suggesting a reduced mental search set size due to reduced interference from the nontarget items (Bäuml and Kliegl, 2013; Lehman et al., 2014).

With respect to encoding accounts of interpolated testing, a strategy-change explanation has been put forward (Chan et al., 2018). In support of this account, Chan et al. recently showed that the PI-reducing effects of interpolated testing may occur because testing, but not restudy, of the prior nontarget material sensitizes subjects to the structure of the study material. In this study, target and nontarget lists were interrelated with each list containing several exemplars from the same semantic categories (e.g., from the categories *animals*, *fruits*, etc.). Results consistently showed that, relative to interpolated restudy, interpolated testing not only increased the number of correctly recalled target items, but also led to higher levels of category clustering, indicating that subjects enhanced semantic organization across lists. Arguably, interpolated testing may have made it more likely that, during study of the target list, subjects were reminded of the nontarget lists' previous exemplars from the same categories, thus becoming better aware of the overall structure of the study material. Behaviorally, evidence for a reset-of-encoding view of the effects of interpolated testing is scarce to date and comes from a single study only, which, relative to a restudy condition, reported somewhat larger recall enhancement for the target list's early items than the list's middle and late items in response to interpolated testing (Pastötter et al., 2018).

4.3. Neural correlates

Three studies using EEG to measure and analyze brain oscillations during item encoding have thus far examined PI buildup in multiple-list learning. In particular, oscillatory activities in the theta (5-8 Hz) and alpha (10-13 Hz) frequency bands were found to increase during encoding of multiple lists (Pastötter et al., 2008, 2011). Because increases in theta activity in the human EEG have been linked to memory load (Jensen and Tesche, 2002; Onton et al., 2005; Sederberg et al., 2006) and increases in alpha activity to inattention (Klimesch, 2012; Palva and Palva, 2007), these findings suggest that the preceding encoding of (nontarget) material can lead to high memory load and inattention and thus impair subsequent encoding of (target) material, which may induce PI. Kliegl et al. (2015) replicated the finding, and additionally showed that individuals with high working memory capacity reveal a less pronounced increase in theta power from nontarget to target lists than individuals with lower working memory capacity, suggesting that individuals with high working memory capacity suffer less from PI-related memory load increases and inattention than the latter group.

Several imaging studies have also examined neural correlates of PI release in multiple-list learning. For instance, the PI-reducing effect of the forget cue in directed forgetting has been studied using fMRI as well as brain oscillations. The two methods were explored during item encoding. One study examined the effects of the forget cue by simultaneously recording participants' EEG along with fMRI while subjects studied the nontarget list first and the target list second (Hanslmayr et al., 2012). Analysis of oscillatory brain activity showed increased alpha power from the encoding of the nontarget to the encoding of the target list in the remember condition – indicating the buildup of PI (see preceding paragraph). In contrast, there was no influence of list on encoding in the forget condition, suggesting that the forget cue may enhance subsequent encoding via an encoding reset. In addition, there was a decrease in alpha phase coupling between electrode sites in the forget condition, which replicated results from previous work (Bäuml et al., 2008) and predicted the impaired recall of the nontarget items. FMRI analysis showed a BOLD signal increase in the forget relative to the remember condition in the left dorsolateral PFC, a brain region repeatedly associated with memory control (Conway and Fthenaki, 2003; Depue, 2012). This BOLD signal increase correlated with the decrease in neural synchrony in the forget condition and might reflect the unbinding of the to-be-forgotten nontarget items via a prefrontally driven downregulation of the cortical network representing those items.

One further study has examined the neural underpinnings of the PI-reducing effects of induced context change. In this study, Pastötter et al. (2008) recorded subjects' EEG during item encoding and analyzed brain oscillations. Subjects studied two lists of unrelated items, and internal context was either changed after study of the initial nontarget list by asking subjects to engage in an imagination task, or the subjects' context remained largely unchanged by asking them to engage in a neutral counting task. Analysis of oscillatory brain activity showed an increase in the theta and alpha frequency bands from the encoding of the nontarget list to the encoding of the target list when context remained largely unchanged between study of the two lists – which again reflects PI buildup – but found no such increase (or even a slight decrease) in theta and alpha power when context was changed. Furthermore, individual participants' alpha power during the encoding of the target list showed a negative correlation with the magnitude of the PI-release effect. These findings are in line with the reset-of-encoding view, suggesting that memory load and inattention may increase from the encoding of the nontarget list to the encoding of the target list, but that an interlist context change may reset the encoding process. Further analyses showed that there was no reduction in alpha phase coupling between electrode sites when context was changed between lists, which differs from PI release as it arises in response to a forget cue (see preceding paragraph). The absence of such an inhibitory signature suggests that enhanced list discrimination may have a different cause after induced context change than in response to a forget cue, and may be mediated by a context drift mechanism in the one case but contextual unbinding in the other.

Pastötter et al. (2011) investigated the neural effects of interpolated testing on PI release by applying an interpolated-testing task, and recording EEG while participants studied five lists of words – four nontarget lists and a final target list. Following study of each of the four nontarget lists, subjects either engaged in interpolated distractor activities, interpolated restudy, or interpolated testing. Behaviorally, results demonstrated the PI-reducing effect of interpolated testing relative to interpolated restudy and interpolated distractor activities. Analyzing brain oscillations, the findings showed a gradual increase in alpha band activity from the encoding of the first nontarget list to the encoding of the target list in the restudy and distractor conditions – thus once again demonstrating PI buildup. Critically, this rise in alpha power was eliminated with interpolated testing, leading to similar alpha power levels across all five study lists. Because high levels of alpha power have been linked to inattentional encoding, these findings indicate that attention levels deteriorated in the restudy and distractor conditions from the encoding of the first nontarget list to the encoding of the target list, whereas no such deterioration arose with interpolated testing. Interpolated testing thus appears to reset the encoding process for each single study list, and make the encoding of the target list as effective as the encoding of the earlier nontarget lists.

4.4. Interim summary

PI buildup in multiple-list learning may result from problems arising at both the encoding and retrieval stages. Regarding retrieval, behavioral results from research analyzing response latencies as well as prior-list intrusions provide evidence that prior nontarget encoding may impede participants' ability to limit their memory search to the target items. Regarding encoding, behavioral work indicates that decreasing attentional resources from the initial nontarget encoding to the later target encoding may also play a role. Behavioral studies on PI release show that directed forgetting, a change in context, and interpolated testing can all improve both encoding and retrieval of the target material. For all three release methods, there is evidence that the methods can enhance retrieval of the target material by enabling a more focused memory search at test, and can enhance the encoding of the target material – either as a result of an encoding reset and/or a change in encoding strategy. Imaging studies on PI buildup show that neural indices of inattention and memory load, like oscillatory alpha and theta power, increase with nontarget encoding, thus providing evidence for impaired target encoding. Activity in the lateral PFC may also influence the encoding of the target information. Regarding PI release, imaging studies analyzing brain oscillations have provided support for the view of an encoding reset and suggest that the three release methods can prevent the buildup of inattention from the encoding of the nontarget to the encoding of the target list.

5. Summary

5.1. Principal findings and explanations of PI buildup and release

Research from the past eight decades has demonstrated that PI buildup as well as release from PI are very robust findings that arise across a wide variety of experimental tasks, learning conditions, and study materials. This research has provided a number of indices of PI buildup, at both the behavioral and the neural level. Behaviorally, the studies have shown that the preceding encoding of other material can reduce recall of the target material, lead to intrusions from the preceding material during target recall, and slow the retrieval process for the target information. Neurally, EEG work has demonstrated that oscillatory alpha power during target encoding increases with nontarget encoding, and fMRI studies have found that activity in the lateral PFC is related to the amount of prior nontarget learning. Similarly, employing a wide range of possible release methods – for instance, detecting change in materials between nontarget and target encoding in paired-associate learning, content change in the Brown-Peterson task, or interpolated testing in multiple-list learning – several indices of PI release have emerged. PI release methods have been shown to increase recall of the target material, reduce intrusions from the prior lists during target recall, and speed up the retrieval process for the target information. They have also been found to decrease oscillatory alpha power during target encoding and to create activity in the lateral PFC. Thus, in tendency, the release methods directly reduce, or even eliminate, the original effects induced by nontarget encoding.

The results on PI buildup and release arose by employing three experimental tasks – paired-associate learning, the Brown-Peterson task, and multiple-list learning – that differ in a number of ways from each other. For instance, while in paired-associate learning recall of the target information depends heavily on the associated stimulus term serving as retrieval cue, in the Brown-Peterson task and in multiple-list learning the temporal context at test serves as the primary cue for recall of the target information; or, while paired-associate learning and multiple-list learning reflect typical long-term memory tasks, the Brown-Peterson task is more similar to a typical short-term memory task. Moreover, there are not only differences in the nature of the three tasks but also differences in the research strategies employed to study PI buildup and release in the single tasks. For instance, while in both paired-associate learning and the Brown-Peterson task degree of learning manipulations and spaced versus massed learning have played an important role in the study of PI – and in the Brown-Peterson task a strong additional emphasis of the experimental work has been on the role of content switch for PI buildup and release – in multiple-list learning the focus has particularly been on PI release methods (for an overview of principal findings in the three tasks, see Table 1). Thus, a priori, there would be reason to expect some variation in arising suggestions on PI buildup and release across the three experimental tasks.

Against this background, it seems quite noteworthy that indications on the cognitive and neural processes underlying PI buildup and release show considerable overlap between the single tasks. Above all, the findings nicely converge on the view that, in general, PI reflects an impairment at both the encoding and the retrieval stage of our memory. At the retrieval stage, the preceding encoding of nontarget material induces a discrimination problem at test. In fact, results from all three experimental tasks indicate that recall at test can suffer from the coactivation of the preceding nontarget material, which gets included into the mental search set and leads to less focused memory search for the target material. In addition, competition from the nontarget material can arise, which leads to blocking of the target material and thus impedes recall performance. At the encoding stage, the preceding encoding of other material attenuates attentional resources for target encoding and leads to impaired memory representations of the target material.

Similar to PI buildup, PI release also emerges through changes at both the encoding and the retrieval stage. At the retrieval stage, PI release methods have been found to largely prevent the nontarget items from being included into the mental search set at the time of test, thus enabling a more focused search for the target items. At the encoding stage, the release methods lead to a reset of the encoding process – which can directly counteract the encoding impairment induced by the nontarget encoding – or cause a change in encoding strategy – which can circumvent the encoding deficit by using more elaborated encoding strategies. Finally, PI release can arise from a mixture of encoding and retrieval mechanisms, as may occur when subjects are reminded of the nontarget information while encoding the target information and recollect the reminding later at test.

5.2. Contributions of single tasks and study lines

Although the findings on PI buildup and release thus paint a relatively consistent picture regarding the roles of encoding and retrieval processes, the empirical contributions of the single experimental tasks to this picture vary to some degree (see Table 1). Indeed, there is variation in the contributions of behavioral versus imaging studies and variation in emphasis on encoding versus retrieval factors. For instance, for paired-associate learning, there is a larger number of behavioral than imaging studies examining PI buildup and release, with behavioral studies focusing mostly on the role of retrieval processes and imaging work showing more of an interest in the contribution of encoding processes. For the Brown-Peterson task, there is an abundance of behavioral studies on both PI buildup and release, but there is also a good number of fMRI and PET studies; both behavioral and imaging work have mostly investigated retrieval processes, and have only rarely addressed encoding processes. In contrast, for multiple-list learning, there are relatively few studies on PI buildup, but a relatively high number of both behavioral and imaging studies examining release methods; while the behavioral work has mostly provided evidence for retrieval factors in PI buildup and release, the imaging work has had a stronger focus on the encoding factors.

Table 1
Chronology of principal PI findings from behavioral and imaging studies for paired-associate learning, the Brown-Peterson task, and multiple-list learning.

Task	*Finding*	*Reference(s)*
BPT, PAL	PI increases with increasing length of the retention interval (B)	Underwood (1948); Koppenaal (1963); Dallet (1964)
BPT, PAL	Recall of target material decreases with the number of study cycles on the nontarget material and increases with the number of study cycles on the target material (B)	Underwood (1949); Fuchs & Melton (1974); Anderson (1983)
BPT	PI reduction can be achieved when the content of the study material is changed from the encoding of the nontarget list(s) to the final target list, and when the change is made explicit to the subjects (B)	Wickens et al. (1963); Gardiner et al. (1972); Wixted & Rohrer (1993)
BPT, PAL	Increasing the lag between study of the nontarget material and study of the target material promotes recall of the target material (B)	Peterson & Gentile (1965); Underwood & Freund (1968); Kincaid & Wickens (1970)
BPT	Pupillary size during target encoding increases with the amount of previously learned nontarget material (B)	Kahneman & Beatty (1966)
PAL	Memory for target items benefits when the nontarget items have been learned in a spaced rather than a massed schedule (B)	Underwood & Ekstrand (1966)
MLL	A cue to forget previously studied nontarget material prior to study of the target material can lead to PI release (B)	Bjork et al. (1968)
MLL	A change in context between study of the nontarget material and study of the target material can induce PI reduction (B)	Dallet & Wilcox (1968); Sahakyan & Kelley (2002)
BPT	A content switch does not seem to induce a reduction in pupillary size during target encoding (B)	Engle (1975)
BPT, MLL	Recall of the target list slows down when other lists have previously been learned (B)	Wixted & Rohrer (1993); Unsworth et al. (2013); Kliegl et al. (2015)
PAL	Activity in the lateral PFC is increased during encoding of A-D interference pairs, relative to completely new C-D pairs (I)	Dolan & Fletcher (1997)
BPT	Greater activation in the ventrolateral PFC arises for recent-negative than nonrecent-negative probes (I)	D‘Esposito et al. (1999); Postle et al. (2004);
BPT	Individuals with high working-memory capacity show increased PI buildup in the presence relative to the absence of a secondary task during nontarget encoding (B)	Kane & Engle (2000)
PAL	Lateral PFC shows increased activity when, at the time of test, participants retrieve A-D pairs after prior A-B encoding (I)	Henson et al. (2002)
MLL	Asking subjects to use a particular encoding strategy can eliminate the PI-reducing effect of providing a forget cue or inducing a change in mental context (B)	Sahakyan & Delaney (2003)
BPT	The difference in reaction time between recent-negative and nonrecent-negative probes is positively correlated with the size of activation in the ventrolateral PFC (I)	Badre & Wagner (2005)
MLL	Oscillatory activities in the theta (5-8 Hz) and alpha (10-13 Hz) frequency bands increase during encoding of multiple lists (I)	Pastötter et al. (2008); Pastötter et al. (2011)
MLL	Interpolated testing can reduce the number of intrusions from the prior nontarget lists when the target list is tested (B)	Szpunar et al. (2008); Pastötter et al. (2011)
PAL	Prior experience with PI can reduce its detrimental effect on memory (B)	Jacoby et al. (2010); Wahlheim & Jacoby (2011)
PAL	Greater activation in the posterior hippocampus during the encoding of the A-D pairs is associated with improved final recall of the originally studied A-B pairs (I)	Kuhl et al. (2010)
MLL	A forget cue leads to a more pronounced PI release for early than middle and late target items (B)	Pastötter & Bäuml (2010); Pastötter et al. (2012)
MLL	Alpha power increases from nontarget to target encoding in the absence, but not presence, of interpolated testing (I)	Pastötter et al. (2011)
MLL	Alpha power increases from nontarget to target encoding in the absence, but not presence, of an interlist forget cue (I)	Hanslmayr et al. (2012)
MLL	FMRI analysis shows a BOLD signal increase in the left dorsolateral PFC in the presence, relative to the absence, of a forget cue (I)	Hanslmayr et al. (2012)
MLL	A forget cue, a change in mental context, and interpolated testing all speed up recall of the target items (B)	Bäuml & Kliegl (2013)
PAL	Proactive facilitation can arise when changes in responses between nontarget and target material are detected and later recollected (B)	Wahlheim & Jacoby (2013); Jacoby et al. (2015)
PAL	Detection and recollection of change enhances list discrimination at test (B)	Jacoby et al. (2013)
MLL	Warning subjects prior to study of the target list that the list will later be tested can promote target recall (B)	Weinstein et al. (2014)
MLL	Subjects with high working memory capacity exhibit a less pronounced increase in theta power from nontarget to target encoding than subjects with lower working memory capacity (I)	Kliegl et al. (2015)
PAL	‘Task-level’ (but not ‘item-level‘) memory reactivation of A-B pairs during the encoding of A-D pairs can predict subsequent memory for a given A-B pair (I)	Koen & Rugg (2016)
MLL	Interpolated testing can lead to higher levels of category clustering (B)	Chan et al. (2018)
MLL	Interpolated testing can lead to a slightly more pronounced PI release effect for early than middle and late target items (B)	Pastötter et al. (2018)

Differences in contributions between the behavioral and the imaging work do not only arise between tasks but do also arise between PI buildup and release. Indeed, with regard to PI buildup, there is a plethora of behavioral work on the role of impaired discrimination – and increased competition – between the nontarget and target materials, whereas barely any imaging studies thus far have examined neural correlates of such retrieval problems. In contrast, there is more of a balance between behavioral and imaging studies regarding the role of encoding processes in PI buildup, with a number of studies from both lines of research providing evidence that nontarget encoding decreases attentional resources. With regard to PI release, behavioral work has particularly increased our knowledge about the role of retrieval processes, while, overall, imaging work has provided insights with respect to both encoding and retrieval processes. These differences point to critical empirical gaps in current research on both PI buildup and release. One such gap is missing imaging work on retrieval processes in buildup of PI; here further work is required, for instance, to identify neural correlates of impaired discrimination. Another gap is missing behavioral work on encoding processes in release from PI; here further work should identify critical processes and relate them to existing neural findings.

5.3. Future directions

As already emphasized above, the previous PI studies employed somewhat different research strategies across experimental tasks. Although these studies did not lead to highly diverging results regarding the processes mediating PI buildup and release, it would be important if future research created a stronger overlap in findings across tasks. For instance, degree of learning manipulations and spaced versus massed learning have been extensively studied in paired-associate learning and the Brown-Peterson task but should also be studied in multiple-list learning. Chan et al. (2018) made a first step into this direction by showing that the effects of interpolated testing do not change when a longer lag between study of the nontarget and study of the target material is introduced. However, further steps are necessary to see whether results generalize to other release methods.

Similarly, the success of a wide variety of methods to induce PI release has well been demonstrated in multiple-list learning but the effects of the same release methods should be examined in paired-associate learning and the Brown-Peterson task as well. Indeed, there is hardly any work to date on directed forgetting and induced context change in paired-associate learning, examining how such release methods influence recall of the A–D pairs after study of the A–B pairs. Given that both a forget cue and induced context change are assumed to impair access to the previously studied nontarget material, change detection, for instance, may be reduced during A–D learning, and the two ‘PI release methods’ may therefore turn out to have detrimental, rather than beneficial effects in this task.

Finally, the balance between contributions of behavioral versus imaging work and the study of encoding versus retrieval processes should be improved in future work. Accordingly, future EEG and imaging studies may like to examine retrieval processes in buildup of PI to identify neural correlates of impaired discrimination, and future behavioral work may like to examine encoding processes in release from PI and relate them to existing neural findings. Gathering findings along these lines would substantially enrich the empirical basis for our understanding of PI buildup and release, so that sustainable conclusions could be drawn about the possible influence of experimental task. Such knowledge would lead to a more complete understanding of PI buildup and release than is possible on the basis of the current findings.

6. Conclusions

The research reviewed here suggests that PI release methods can oppose the problems that prior encoding of nontarget material induces for both the encoding and retrieval of target information. Prior nontarget encoding typically increases inattention, and PI release methods can neutralize such tendency, for instance, by inducing a switch to a superior encoding strategy or by resetting the encoding process. Prior nontarget encoding can also lead to a less focused memory search at test, but PI release methods can counteract this challenge by either enhancing discrimination between the target and nontarget material or by integrating the target and nontarget material. Current research provides reasonable support for this overall picture of PI buildup and release, but future work is warranted to examine the picture in more detail. Until then, the suggested picture may serve as a useful framework to describe PI buildup and release and to deduce testable hypotheses on the two effects.

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