Psychonomic Bulletin & Review (2022) 29:753–765
https://doi.org/10.3758/s13423-021-02022-8

THEORETICAL/REVIEW

Unraveling the benefits of experiencing errors during learning: Definition, modulating factors, and explanatory theories

Yeray Mera[1] · **Gabriel Rodríguez**[1] · **Eugenia Marin-Garcia**[1]

Accepted: 28 September 2021 / Published online: 24 November 2021

Abstract

Making errors is part of human nature, and it is thus important to know how to get the best out of them. Experimental evidence has shown that generating errors can enhance learning when these are followed by corrective feedback. However, little is known about the specific conditions and mechanisms that underlie this benefit of experiencing errors. This review aimed to shed some light on this type of learning. First, we highlight certain conditions that may influence errorful learning. These include the timing of corrective feedback, error types, learner awareness about errorful learning, motivation to learn the study material, differences in special populations (e.g., amnesia), incidental versus intentional encoding, the importance of selecting an appropriate final test procedure, whether the study material needs to be semantically related, and if it is necessary to recover the previous errors at the time of retrieval. We then consider four explanatory theories of errorful learning: (1) The *Mediator Effectiveness* hypothesis, (2) the *Search Set* theory, (3) the *Recursive Reminding* theory, and (4) the *Error Prediction* theory. According to these theories, two factors are decisive for observing the benefits of errorful learning: the level of a pre-existing semantic relationship between the study materials, and whether the error must be explicitly recovered on the final test. To conclude, we discuss some limitations of using a *pretesting* procedure to study errorful learning and we reflect on further research. This review brings us closer to understanding why experiencing errors confers a memory advantage.

Keywords Errorful learning · Learning from Errors · Unsuccessful retrieval · Pretesting

Introduction

Committing errors and managing failure are basic elements of learning processes but producing errors while learning has traditionally been considered detrimental for the recovery of the correct answer. This assumption was based on the *Interference Theory* (Melton & Irwin, 1940; Postman & Underwood, 1973), which proposes that experiencing errors increases the distinctiveness of those items that compete with the correct answer at retrieval. This has led to a preference for errorless learning in educational settings, which was typically thought to provide the most effective outcomes (Stevenson & Stigler, 1994; Tulis, 2013). More recent proposals about this perspective argue that errors are highly salient events that capture attention and divert attentional resources from the task, impairing subsequent performance (Houtman & Notebaert, 2013; Notebaert et al., 2009).

However, in recent decades, an increasing body of evidence has emerged to suggest that experiencing errors during learning, as long as corrective feedback is given, enhances subsequent memory retrieval (e.g., Metcalfe, 2017). There is considerable support for the beneficial effects of failed testing on learning, which have been demonstrated with a range of learning materials, including word-pairs (Clark, 2016; Grimaldi & Karpicke, 2012; Knight et al., 2012; Kornell et al., 2009; Metcalfe, 2017; Potts & Shanks, 2014; Seabrooke et al., 2019a, b; Slamecka & Fevreiski, 1983; Vaughn & Rawson, 2012), along with more ecologically relevant materials such as facts (Kang et al., 2011; Kornell et al., 2015; Richland et al., 2009); sentence translations (Guzmán-Muñoz, 2020); texts (van Loon et al., 2015); or definitions (Metcalfe et al., 2009).

It is important to distinguish errorful learning from other, related effects. In particular, it is well established that testing during encoding of information is more beneficial than re-studying, which is referred to as the *Testing effect*

✉ Eugenia Marin-Garcia
emaringar@gmail.com

1 Psychology School, University of the Basque Country (UPV/EHU), Avenida Tolosa, 70, 20018 San Sebastián, Spain

or *Retrieval practice* (see Roediger & Karpicke, 2006, for a review). In addition, the *Generation effect* shows that generating information in response to a cue leads to better memory than simply reading it (Slamecka & Graf, 1978). In both cases, the benefit for long-term memory is related to active cognitive processes such as generating or attempting to recall the correct answer. Thus, these effects are related to successful generation/recovery. In contrast, learning based on experiencing errors is related to unsuccessful experience, which is the main focus of this research. In addition, the *hypercorrection effect* is a phenomenon related to errorful learning described by Butterfield and Metcalfe (2001). This effect suggests that high-confidence errors are more likely to be corrected than low-level confidence errors. This effect is well established in behavioral (Butterfield & Metcalfe, 2006; Iwaki et al., 2013; Metcalfe et al., 2012, 2015; Metcalfe & Miele, 2014) and neuroimaging studies (Metcalfe et al., 2012).

In previous research that has explored why experiencing errors enhances learning, *pretesting* is the most frequently used paradigm (e.g., Potts & Shanks, 2014; Richland et al., 2009; Seabrooke et al., 2019a, b; Zawadzka & Hanczakowski, 2019), also referred as *unsuccessful retrieval* (Kornell et al., 2009) and *failed retrieval* (Tanaka et al., 2019). In this paradigm, participants are encouraged to generate an answer before studying it. Thus, since there is no pre-exposure to the learning material, participants are almost always incorrect and make many errors (see Fig. 1). The usual result is that *pretesting* unknown information, even when many errors are being committed, is more beneficial than simply studying it.

Whilst the benefit of errors for long-term memory is well established, it is critical to understand the underlying mechanisms of this effect and the conditions under which such errors would be beneficial for future memory performance. This is not only relevant from a theoretical point of view but also from a practical perspective. In fact, it is in educational settings where it becomes of great importance to know why and when experiencing errors during learning benefits memory. This information would help teachers and students to change their mindset and attitudes towards errors, from considering them a sign of failure to including errors as part of constructive learning (Clark, 2016; Metcalfe, 2017; Wong & Lim, 2019).

Modulating factors in the effect of experiencing errors

It is important to understand the specific conditions in which experiencing errors could benefit memory and to explore which factors may influence this benefit. Presumably, observing an increase or attenuation of this effect could depend on a complex dynamic between several factors rather than the influence of a single factor (Clark, 2016; Tanaka et al., 2019; Vaughn & Rawson, 2012).

Corrective feedback

In order to optimize the benefit of experiencing errors, it appears to be essential that learners receive corrective feedback after committing the error, so that the correct answer can be encoded (Huelser & Metcalfe, 2012; Metcalfe et al., 2012; Metcalfe & Kornell, 2007). This is related to the fact that errors are not likely to be spontaneously corrected without feedback (Butler et al., 2008). Furthermore, corrective feedback must explicitly include the correct answer. It is not helpful to simply inform the learner as to whether or not their response is correct (Pashler et al., 2005). With regard to the timing of the feedback, it is not clear whether the moment at which feedback is given after an error is decisive for increasing learning. Moreover, it is not well understood if there is a specific time window in which the error can be corrected, outside of which the feedback is no longer effective. The dominant view is that in order to benefit from experiencing errors, corrective feedback needs to be provided shortly after the error is committed (e.g., Grimaldi & Karpicke, 2012; Hays et al., 2013; Vaughn & Rawson, 2012). However, this remains a matter of debate since contradictory results have been found (Kornell, 2014; Metcalfe et al., 2009). In this regard, Kornell (2014) conducted a series of *pretesting* experiments and found that generating errors with more complex and meaningful material (e.g., trivia questions) enhanced correct recall even when the corrective feedback

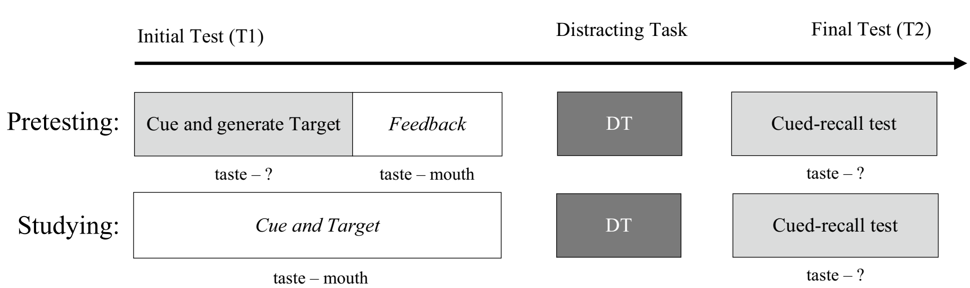

Fig. 1 Pretesting procedure

was delayed. But less meaningful material (e.g., word-pairs) did not show such benefit. This is probably due to the fact that more meaningful learning material may activate a richer semantic network, which would enhance more elaborative retrieval. In any case, regardless of the timing of the feedback, providing corrective feedback results in better performance than when no feedback is given.

Related to this, a further relevant question that arises is whether the time interval between the learning phase (when an error occurs and when feedback is given) and the moment of the final test has an impact on subsequent retrieval. Classic studies (e.g., Ebbinghaus, 1885) demonstrated that the speed of forgetting depends on different variables such as time since learning and that this relationship follows a logarithmic function, findings that have recently been replicated (Murre & Dros, 2015). However, it is not clear if this relationship operates in the same way with correct responses and error-feedback-corrected responses. Future research should study the moment at which the feedback is given whilst comparing two conditions: immediate feedback and delayed feedback. Furthermore, it is important to study if this time window of feedback is related to both the learning session and the final test (see Fig. 2 for a schematic representation of such an experimental procedure).

Error types

In this context, errors are defined as objective outcomes that involve incorrect responses. Errors can be classified depending on learners' intentions and motivations when it comes to erring. In this regard, a key distinction has been made between *slips* and *mistakes*. Slips refer to the cases in which learners execute an incorrect response accidentally, while mistakes refer to errors that result from incorrect knowledge (Norman, 1981; Wong & Lim, 2019). The present review is focused on errors. During information retrieval, errors can occur in two different ways: by omission, when participants are not able to recall any response and leave the answer blank; and by commission, when an erroneous response is given. Slamecka and Fevreiski (1983) analyzed the effect of commission errors compared to omission errors, and their results revealed that, compared with omission errors, commission errors resulted in better subsequent performance. Another relevant factor in errorful learning is whether the error should be experienced personally to enhance long-term memory. Research shows that in order to be most helpful for learning, errors must be self-generated rather than be observed in others, or be presented as mistaken items (e.g., Grimaldi & Karpicke, 2012; Metcalfe & Xu, 2018). Metcalfe and Xu (2018) showed that generating errors oneself compared with hearing another person committing errors out loud, was beneficial for later correct recall. If the person was not the one who actively committed the error, such benefit was not found. Thus, it is important to analyze the type of errors being committed during testing and how such errors have an impact on performance.

Metamemory about errorful learning

Flavell and Wellman (1977) defined metamemory as knowledge about our own memory and its processes of encoding, storing, and retrieving information. Thus, metamemory is related to knowledge about the function of memory and the strategies that can be used to improve it (Metcalfe & Shimamura, 1994). This includes the estimation of our learning capacity, the selection of encoding and retrieval strategies, or the awareness of what we know and what we do not know. In general, learning conditions that facilitate a rapid improvement in performance are often perceived by learners as being more effective. However, conditions that create challenges and increase difficulty have been shown to optimize long-term retention (E. L. Bjork & Bjork, 2014). Thus, certain difficulties are considered to be desirable for increasing long-term learning. In relation to this issue, Huelser and Metcalfe (2012), using a *pretesting* paradigm, asked participants about which learning condition they thought led to better performance. The results showed that a significantly higher percentage of

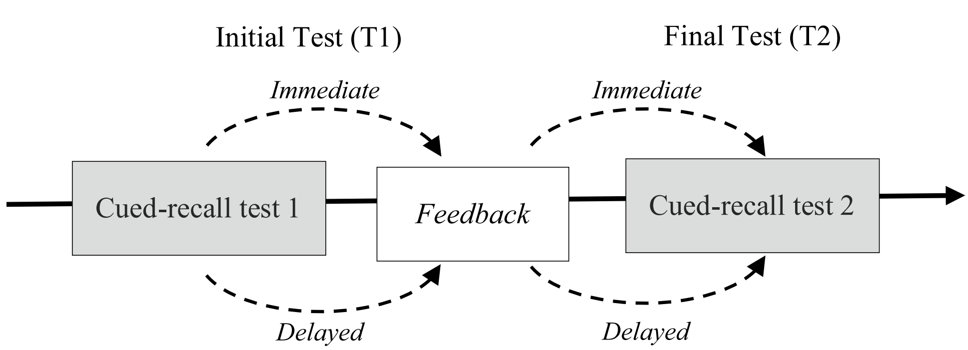

Fig. 2 Experimental procedure comparing delayed vs. immediate feedback and delayed vs. immediate final test

participants believed that the errorless learning condition was more effective than errorful learning, even when they had just experienced the benefit of making errors (see also Yang et al., 2017). Learners tended to believe that making errors during tests made them learn less whilst in fact they were actually learning more. Thus, there is a dissociation between learners' judgments about learning and their actual performance. However, it has been shown that learners do not need to be aware of the positive effect of the errors to benefit from them (Huelser & Metcalfe, 2012). This lack of awareness, however, could influence the learning procedure chosen by both learners and teachers and it could partly explain the traditional avoidance of errors in educational settings (Stevenson & Stigler, 1994; Tulis, 2013). Indeed, research conducted by Pan et al. (2020) examined the awareness of the benefit of errorful learning among students and teachers. Students reported a generalized aversion towards making errors during learning events. However, they also indicated making the effort to learn from those errors when they occurred (e.g., analyzing the corrective feedback and their own committed errors). Thus, it seems that the benefits of errorful learning are unappreciated, and that errors are avoided.

Motivation towards the to-be-learned material

Another factor that could impact the dynamics of experiencing errors during testing is the extent to which participants are motivated to learn the material. Often, the material may not be interesting for learners, particularly in experimental contexts. In this regard, in a *hypercorrection effect* study conducted by Iwaki et al. (2013), participants' usefulness judgments of the proposed material were analyzed. The results showed that the benefit of experiencing errors during testing was modulated by the participants' perceived usefulness of the study material, leading to better recall at a later test when the material was considered practical and useful. Similarly, another study revealed that error generation increased correct performance at the final test, especially with those stimuli that participants considered more motivating (Seabrooke, Mitchell, et al., 2019b). This motivational factor could also be linked to an increase in curiosity to the corrective feedback that takes place after an error is committed during learning (Potts et al., 2019).

Population

Most of the studies reviewed above used neurologically typical younger adults as participants. However, some research studies have been conducted on the effects of experiencing errors during learning with different populations (Cyr & Anderson, 2012, 2015; Huelser & Metcalfe, 2012; Metcalfe et al., 2009; Metcalfe et al., 2015; Metcalfe & Finn, 2012). Regarding different age groups, for instance, Cyr and Anderson (2012, 2015) studied healthy older adults and their findings revealed that experiencing errors during encoding could help to diminish age-related typical declines in episodic memory. This advantage resulting from experiencing errors was also found among school-age (11–13 years old) children, using general information questions (Metcalfe & Finn, 2012), and with semantically related word-pairs with 5-year-old children (Carneiro et al., 2018). Nevertheless, errors may have a detrimental effect on special populations. Some studies (Mueller et al., 2007) have argued that errorless learning may be more effective for children with autism spectrum disorders, which is characterized by rigid adherence to rules, a difficulty in shifting behavioral repertoires, and often problematic behaviors in response to failures. Furthermore, some studies suggest that experiencing errors may be disadvantageous for people with memory and cognitive impairments (e.g., Alzheimer's disease, and amnesia). For example, Baddeley and Wilson (1994) conducted a series of experiments showing that patients with amnesia benefited more from errorless learning than when experiencing errors. These authors argued that the benefit of errorless learning could be based on implicit memory, which does not require a conscious recollection of information, but simply tends to activate the dominant response (see Clare & Jones, 2008, for a review). Thus, prior errors may create more interference for individuals with memory impairments, and this would explain why such learners might benefit more from avoiding errors. However, this is still not clear. These results may vary depending on the severity of the amnesia, the characteristics of the task, and how memory is assessed (Middleton & Schwartz, 2012). In these cases, short-term, errorless learning produces greater familiarity with the study material and leads to better performance. However, in long-term learning, it seems that errorful conditions lead to more robust learning (Hunkin et al., 1998; Squires et al., 1997). These factors could explain the variability of the results found when using errorful learning in special populations. Thus, even for memory-impaired patients, experiencing errors during learning could increase long-term gains when compared with errorless learning.

Incidental versus intentional nature of encoding

It is important to consider the influence of the nature of the encoding on the benefits produced by errors. The studies mentioned above have focused on intentional encoding in which participants are aware that they are acquiring information and that they will have a subsequent memory task to test their learning. However, incidental encoding implies unawareness of information acquisition and the subsequent memory task. It is of interest to analyze whether the benefit of experiencing errors is modulated by the nature of the encoding. For example, in their study, Decker et al. (2020) used a categorization task in which participants encoded images while categorizing them as, for example, living or non-living, in order to produce incidental encoding, after which they performed a surprise old/new recognition memory task. The results were inconsistent; in one experiment commission errors were remembered marginally better than baseline memory and, in another experiment, there was no difference between memory for errors relative to baseline. Thus, further research is needed in order to understand the effect of incidental encoding when using errorful learning.

Final test format

The final test procedure is another factor that could play a role in the dynamics involved in the benefits of experiencing errors. Thus, different final test procedures have been used to study the benefit of experiencing errors during learning. The most common procedure is cued-recall, in which a cue is presented and participants are asked to remember the associated target (e.g., Huelser & Metcalfe, 2012; Kornell et al., 2009). Other tests have also been used, such as multiple-choice tests, in which the cue is presented and participants are asked to recognize its target among other foils (e.g., Potts & Shanks, 2014); the associative recognition test, in which participants are shown word-pairs and have to decide whether they were presented together in a previous study phase (Seabrooke et al., 2019a, b); the free-recall test, in which participants try to retrieve as many words as they can from the study phase (Clark, 2016); and backward cued-recall, in which the target is presented and participants are asked to remember the cue that preceded it (Clark, 2016). The use of these different procedures for the final test have led to mixed results (Seabrooke et al., 2019a, b). For example, the benefit of experiencing errors have been demonstrated with unrelated material using multiple-choice tests (Potts & Shanks, 2014) but not with cued-recall tests (Huelser & Metcalfe, 2012) or with an associative recognition test (Seabrooke et al., 2019a, b). Therefore, it seems important to consider the selected test format when studying the benefit of committing errors during learning in order to adequately understand the outcomes.

Semantic relationship

Regarding the semantic relationship factor, there are two important questions. The first is whether the semantic relationship between the error and the correct answer is necessary to experience the benefit of the error. The second question is whether the study materials must be semantically related to facilitate errorful learning. With respect to the semantic relationship between the *error and the correct* answer, Huelser and Metcalfe (2012) conducted an experiment to study the strength of a semantic association between the generated error and the correct answer using Latent Semantic Analysis (LSA). This LSA method is used to estimate the degree of semantic proximity between words (Landauer & Dumais, 1997). Results revealed memory advantage only when the generated error had a strong semantic relationship with the correct answer, which would only happen when the word-pairs themselves were also semantically related. When the learning material was semantically unrelated, the generated errors were also unrelated to the correct target. Thus, they were not able to isolate the effect of the error-target relationship in a way that was independent of the cue-target relationship. In fact, in a more recent study conducted by Metcalfe and Huelser (2020), it was showed that errors unrelated to the target could also show *pretesting* benefits. In another study, certain cues were presented (e.g., "*band–*?") and participants were asked to guess the target (e.g., "*drum*") before revealing the correct answer. This target was either semantically related to their guess (e.g., "*guitar*") or unrelated (e.g., "*rubber*"). The results were in agreement with previous findings, showing that final cued-recall accuracy was greater when there was a semantic relationship between the generated error and the correct target (Cyr & Anderson, 2018).

Regarding the semantic relationship between the *study material*, the most widely accepted view is that the benefit of experiencing errors only occurs when such material is semantically related, such as in the case of word-pairs, for example, when there is a semantic association between *the cue and the target* (Grimaldi & Karpicke, 2012; Huelser & Metcalfe, 2012; Little & Bjork, 2016; Seabrooke et al., 2019a, b). In this regard, Grimaldi and Karpicke (2012) employed a standard *pretesting* procedure (see Fig. 1) and compared the effect of the semantic relationship between cues and targets of the word-pairs. Participants were asked to learn a mixed list containing semantically related word-pairs (e.g., "*tide–beach*") and unrelated word-pairs (e.g., "*pillow–leaf*"). One group simply read each pair (e.g., "*tide–beach*" or "*pillow–leaf*"), while the other was encouraged to guess a target in response to a cue (e.g., "*tide–?*" or "*pillow–*?") and both groups were then given the same final cued-recall test across all items. The results showed that generating errors during learning in a *pretesting* paradigm enhanced the final recall of semantically related word-pairs but not of unrelated word-pairs. Thus, it was concluded that a semantic relationship between the cue and the target is needed in order to enhance subsequent retrieval.

Contrary to this viewpoint, Potts and Shanks (2014) proposed that a pre-existing semantic relationship between the study material (*cue and target*) is not necessary to benefit from experiencing errors. In this study, participants learned definitions of very rare English words (e.g., "*valinch–tube*") in a typical *pretesting* paradigm in which participants were asked to guess an answer (e.g., "*valinch–?*") before studying the material. This was compared to a condition in which participants simply read the correct answer. The final test consisted of a multiple-choice question task, in which cues were presented and participants were asked to select the correct target among the other three foils. The results showed that even without a semantic relationship between the cues and targets, experiencing errors during encoding enhanced performance on the final test relative to simply studying the correct answers from the outset. These results were replicated with Basque-English translations (e.g., "*hodei–cloud*"; Potts & Shanks, 2014).

It has been argued that these discrepant results could be related to the specific format of the final test, that is, a multiple-choice versus cued-recall test. In fact, this task requires the recognition of the target among the foils but does not require retrieval of the association between the cue and the target. This associative knowledge refers to the ability to bring the target to mind when the cue is presented, which would only happen once a cue-target association is formed. Some studies have tried to extend the results reported by Potts and Shanks (2014) with unrelated material to test formats that assess associative knowledge, but contradictory results have been found. For instance, Seabrooke et al. (2019a, b) found no *pretesting* effect using a cued-recall test. They concluded that experiencing errors with semantically unrelated material may improve memory for targets and cues in isolation, but not for the association between them. In contrast, Cyr and Anderson (2018) showed that both semantically related and unrelated word-pairs resulted in better performance compared with the errorless condition using cued-recall. They were not, however, able to generalize these results to more complex materials such as Spanish-English false friends. Thus, further research is needed to determine whether the memories for the stimuli presented during the encoding phase are strengthened by error generation in a way that is not measured by those associative tests.

Error recovery on the final test

There is a growing body of research suggesting that, on the final test, learners explicitly recover their previous errors at the same time that they remember the correct answers (Cyr & Anderson, 2018; Knight et al., 2012; Metcalfe & Huelser, 2020). In this regard, Cyr and Anderson (2018) conducted a *pretesting* experiment. First, participants were encouraged to generate guesses in response to cues, after which corrective feedback was given. On the final test, and before attempting to retrieve the correct targets, the participants were asked to recall the errors (guesses) generated for each cue. The results showed that participants were more likely to recover their previous errors than correct targets. These results are consistent with those found by Knight et al. (2012). These authors used a *pretesting* procedure in which learners were asked to generate guesses to cues, before receiving corrective feedback. On the final test, they were then asked to recall the word they guessed earlier for that specific cue, and then recall the correct target. They found that participants were able to recall their guesses on most of the trials, suggesting that the error is activated on the final test. Indeed, a study conducted more recently by Metcalfe and Huelser (2020) showed that memory for the correct answer was enhanced only when the original error was also recovered on the final test. However, a possible limitation of such studies is the inability to establish whether learners actually recall their previous errors, or whether they are generating them from scratch, given that it might be their preponderant response to a given question or cue.

In contrast, other studies have found no evidence to support this idea (Butterfield & Metcalfe, 2001; Metcalfe & Miele, 2014). Butterfield and Metcalfe (2001), in a *hypercorrection effect* study, asked participants to provide three answers on the final test, after which they were required to indicate which of the responses was correct. This manipulation allowed for investigating the mental presence of the original error during the final test. However, their findings revealed that participants did not recover their previous errors. Thus, correct recall was independent of error recovery on the final test. Similarly, in another *hypercorrection effect* experiment conducted by Metcalfe and Miele (2014), participants were requested to provide two answers on the final test, in order to determine whether the original error had been generated as one of those two responses. However, no relation was found between correct recall and the presence of the error as one of these responses. It is possible that these discrepancies are due to the type of instructions given when recovering the error. In the studies by Butterfield and Metcalfe (2001) and Metcalfe and Miele (2014), learners were asked to respond with whatever word came to mind, which can be attributable to implicit memory. In other studies (e.g., Cyr & Anderson, 2018; Knight et al., 2012; Metcalfe & Huelser, 2020), participants were told to explicitly recall their previous erroneous answers. Thus, these differences in the error recovery on the final test could be due to differences in explicit versus implicit memory, an important issue that is worthy of further investigation in future research on errorful learning Table 1.

Theoretical explanations of the benefit of experiencing errors

To understand the advantageous effects of errorful learning, some explanatory theories have been proposed (e.g., Grimaldi & Karpicke, 2012; Kornell et al., 2009; Metcalfe, 2017; Potts & Shanks, 2014). The most compelling theories are the following: The *Mediator Effectiveness* hypothesis,

Table 1 Overview of the modulating factors in the benefits of experiencing errors

Modulating factors
1. Corrective feedback
- Feedback is crucial in order to observe the benefits derived from experiencing errors.
- It is not clear whether experiencing errors would be advantageous when the feedback is given after a long period of time or when the final test is delayed.
2. Error types
- Accidental errors (slips) ≠ errors based on incorrect knowledge (mistakes).
- Learners benefit more from commission errors (incorrect answers) than from omission errors (blank answers).
- Self-generated errors are more beneficial than observed errors.
3. Metamemory unawareness
- There is a dissociation between participants' judgments about learning and their actual performance.
- Learners tend to believe that errorless learning conditions are more beneficial than errorful learning.
4. Motivation towards the to-be-learned material
- Errorful learning is enhanced when using material that participants consider motivating.
5. Population
- Errors may be detrimental in special populations such as children with autism spectrum disorders, and people with severe memory and cognitive impairments, but additional research is needed.
6. Incidental versus intentional nature of the encoding
- Further research is needed to understand the effect of incidental versus intentional encoding errorful learning.
7. Final test format
- The most common procedure is the "cued-recall test" (e.g., "*taste–?*"; correct target: "*mouth*").
- Differences in final test procedures have yielded mixed results. Further research is needed to understand this in greater depth.
8. Semantic relationship
- The most widely accepted view is that it is essential to use semantically related material to benefit from experiencing errors.
- Results are controversial and may vary according to the final test format (multiple-choice task vs. cued-recall).
9. Error recovery on the final test
- Learners recall previous erroneous responses along correct answers at the time of retrieval.
- There are some differences between implicit and explicit error recovery.

the *Search Set* theory, the *Recursive Reminding* theory, and the *Error Prediction* theory. According to these theories, there are two main variables that are decisive in observing the benefits derived from errorful learning: the level of pre-existing semantic relationship between the study materials, and whether the error is explicitly recovered on the final test (see Fig. 3).

First, the *Mediator Effectiveness* hypothesis (Pyc & Rawson, 2010) was originally proposed as an explanation for the *Testing effect* (see earlier definition). This theory suggests that the testing effect is associated with the strengthening of links between cues and targets, creating more effective mediators during retrieval. For example, when individuals attempt to learn the target during word-pair encoding (e.g., "*taste–mouth*"), they generate mediators (e.g., "*bitter*," "*tongue*"), and the recovery of these mediators facilitates the accessibility of the target information on the final test through their associative relationship. This hypothesis provides a possible explanation for errorful learning, in which the committed error may be used as a mediator that aids the recovery of the target. Thus, failed initial retrieval attempts may enhance recovery of the correct target because there are two cues that facilitate the retrieval of the correct target: the cue itself and the error, acting as a mediator. In this regard, Soraci et al. (1999, 1994) proposed a *Multiple-Cue* hypothesis. These authors conducted a series of experiments to study the *Generation effect* (see earlier definition). They found that increasing the number of cues provided during acquisition was also effective in increasing final recall. However, there is some evidence that contradicts the mediator hypothesis. In a series of *pretesting* experiments, Clark (2016) observed that allowing participants to generate richer and more relevant guesses (thus, better mediators) did not improve performance on the final test. With regard to assumptions, the *Mediator Effectiveness* hypothesis predicts that if the error functions as a mediator, it must be recovered on the final test to observe the memory advantage of experiencing errors. And the other prediction is that this benefit is only clear if the errors are semantically related to the correct answer, which would only occur with semantically related study materials (Grimaldi & Karpicke, 2012; Huelser & Metcalfe, 2012).

The *Search Set* theory proposes that retrieval attempts, albeit unsuccessful, trigger a search process through semantically related activated candidates. The *Search Set* includes these candidates and, among them, the correct answer. During feedback, when the correct answer is presented, the encoding of the target among other candidates is reinforced, strengthening the mapping between the cue and the target (Grimaldi & Karpicke, 2012). Thus, the target is encoded more effectively because it has already been partially activated by the error. However, it is unclear why

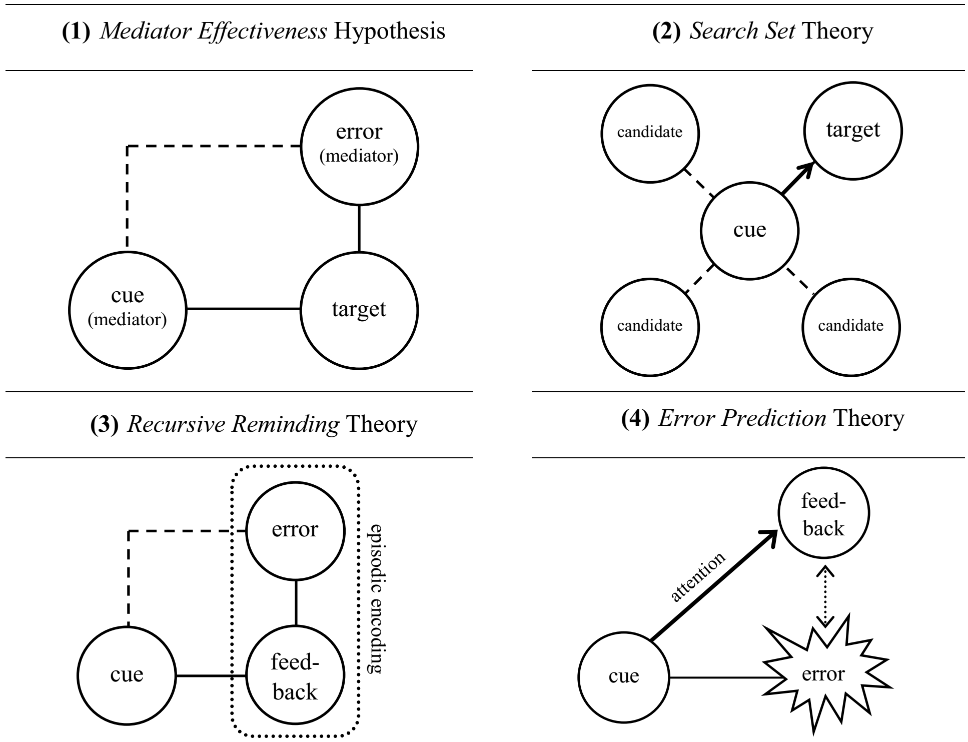

Fig. 3 Graphical illustrations of the theories proposed to explain the benefit of experiencing errors: (1) The Mediator Effectiveness Hypothesis, (2) The Search Set Theory, (3) The Recursive Reminding Theory, and (4) The Error Prediction Theory

this reinforcement is stronger after unsuccessful retrieval attempts. If the mere act of attempting to recall activates the routes to possible answers, there should be no difference between successful and unsuccessful retrieval attempts in terms of their beneficial effect on the subsequent encoding of the target. Additionally, the search for the correct answer might also strengthen the incorrect retrieval routes. These may interfere with the correct cue-target routes, which is incompatible with the beneficial effects of experiencing errors in testing, described above. Regarding this issue, Kornell et al. (2009) and Clark (2016) proposed the existence of an error-suppression mechanism whereby unsuccessful tests could enhance learning by suppressing incorrect retrieval routes. This would make errors less accessible and it would reinforce correct cue-target routes, thus facilitating future correct recall. Given the assumptions of the *Search Set* theory, experiencing errors should only be beneficial when there is a pre-existing semantic association between the study materials (that is, between word-pairs or cues and targets). This idea is based on the fact that with semantically unrelated material, the initial *Search Set* of possible candidates would not include the target. Thus, according to the *Search Set* theory, attempting retrieval during the initial test should only enhance the encoding of the semantically related cue-target pairs. With respect to error recovery, this theory does not assume the need to explicitly recall the error on the final test. Thus, whilst the error could be activated on the final test, its explicit recovery is not necessary. And if there was an error-suppression mechanism, then a decrease in error-related activation would be expected, making it even more difficult to recall the error.

Both the *Mediator Effectiveness* hypothesis and the *Search Set* theory are consistent with the *Spreading Activation* theory, in which semantic information is organized in a network of interconnected nodes where the activation is propagated (Collins & Loftus, 1975). Regarding the *Mediator* hypothesis, since the self-generated error is part of the semantic network of the correct item, the recovery of the previously generated error would also activate the correct answer, through the spread in activation, which would increase the probability of recalling the error. The *Search Set* theory predicts that retrieval attempts would activate items associated with the cue, and through spreading activation, a semantic network of related concepts would be activated providing a route to facilitate the retrieval of the target on the final test.

The *Recursive Reminding* theory (Wahlheim & Jacoby, 2013) bases its explanation of the benefit of experiencing errors on episodic memory, the capacity to explicitly remember specific events in a spatio-temporal context (Tulving, 1972). This theory predicts that memory for the correct answer is enhanced if the original error is recovered at the retrieval stage. In particular, it is suggested that the long-term memory benefits of experiencing errors occur because both the error and the correct response (through feedback) are encoded in the same episodic event, sharing a temporal and spatial context and thus the same encoding details. Thus, during the final test, the error recovery activates the encoding context shared between the correct response and the error, which facilitates access to the correct response. With regard to assumptions, this theory predicts that the error must be recovered on the final test to observe the memory advantage of experiencing errors. However, a pre-existing semantic association is not considered essential and the memory performance of both related and unrelated study materials will benefit from experiencing errors.

Finally, the *Error Prediction* theory argues that failed recovery efforts may benefit memory due to the discrepancy between the errorful outcome of a recovery attempt and the subsequent corrective feedback, which would produce an error signal and enhance attention. Therefore, the encoding of the target would be favored (Grimaldi & Karpicke, 2012). In general, traditional learning theories claim that the amount of learning that occurs during error correction corresponds to the size of the discrepancy between an event and the subject's prior expectations of such an event, which is related to the level of attention commanded by that discrepancy (e.g., Rescorla & Wagner, 1972). In this regard, *adaptive neurocognitive theories* (Decker et al., 2020) suggest that errors produce a cognitive discrepancy that would activate conflict resolution processes, which is thought to increase attention and task engagement (Botvinick et al., 2001; Yeung et al., 2004). First, attention is increased by a process energized by the anterior cingulate cortex (ACC), a brain area involved in cognitive control and conflict monitoring. The ACC would detect errors and signal to other brain regions to increase attention (Yeung et al., 2004). This process would then slow down subsequent responses and improve accuracy (Botvinick et al., 2001). This adaptive neurocognitive theory is also consistent with research findings on errorful learning predictions using the *pretesting* paradigm, which shows that expectancy-violating errors benefit later correct recovery (e.g., Brod et al., 2018).

This *Error Prediction* theory is consistent with the *hypercorrection effect* (Butterfield & Metcalfe, 2001), in which high-confidence errors are more likely to be corrected at a final test than those errors rated with low confidence. The neural basis of the *hypercorrection effect* has been analyzed by comparing differential brain activations between high- and low-confidence errors with functional magnetic resonance imaging (fMRI) (Metcalfe et al., 2012). The results indicate greater activation in the medial frontal cortex including the anterior cingulate (an area associated with surprise, error detection, and attention) and other areas such as the dorsolateral prefrontal cortex and the temporal-parietal junction (TPJ), which are also related to surprise. These results are in agreement with the discrepancy-related explanation, in which increased attention requirements produce deeper encoding of the feedback.

With regard to assumptions, according to the *Error Prediction* theory there is no need for a pre-existing semantic association between the to-be-learned material or an explicit recall of the error on the final test in order to benefit from errorful learning.

In conclusion, regarding the assumption of the semantic relationship between the study materials, both the *Mediator* and the *Search Set* theories consider that the advantage of experiencing errors can only be observed when there is a pre-existing semantic association between the study materials. Regarding the assumption of error recovery, both the *Mediator Effectiveness* hypothesis and the *Recursive Reminding* theory predict that the error must be recovered on the final test to observe a memory benefit. Finally, according to the *Error Prediction* theory, such conditions are not needed to observe the memory benefits resulting from errorful learning.

There is evidence both for and against the previously described explanatory theories, based on two assumptions: semantic relationship of the study material and error recovery on the final test. Concerning the first of these factors, previous studies have stated that errorful learning is only beneficial when the study material is semantically related (Grimaldi & Karpicke, 2012; Huelser & Metcalfe, 2012; Little & Bjork, 2016; Seabrooke et al., 2019a, b). However, this question remains open, since it has also been proposed that semantically related and unrelated material both benefit from experiencing errors (Cyr & Anderson, 2018; Potts & Shanks, 2014). Regarding the role of error recovery, some research suggests that learners need to explicitly recover their previous errors along with the correct answers at the final test in order to benefit from the errorful experience (Cyr & Anderson, 2018; Knight et al., 2012; Metcalfe & Huelser, 2020). But, contrary to this position, other studies did not find such explicit error recovery (Butterfield & Metcalfe, 2001; Metcalfe & Miele, 2014). In the light of these contradictory results, further research is needed to understand the importance of the semantic relationship and error recovery assumptions, which would help to clarify the most plausible explanatory theory.

Limitations and further research

Although *pretesting* is the most frequently used procedure for studying errorful learning, it has some limitations that should be considered for future investigations. First, there is no clear consensus regarding the level of familiarization with the learning material that is needed to consider a wrong answer an error. As in *pretesting*, there is no pre-exposure of the learning material, it has been suggested that those errors may not be genuine errors but merely guesses (Potts & Shanks, 2014). Although this problem is not so relevant with certain study materials such as sentence translation (Guzmán-Muñoz, 2020) or trivia questions (Kornell et al., 2009), it is especially evident with other learning material such as word-pairs in which the incorrect nature of the answers is experimenter-based. Thus, when using a *pretesting* paradigm, it should be considered whether the errors are genuine and require real effortful recovery of the previously learned material, and not just guesses. This is particularly pertinent because the emotional and motivational components involved in genuine errors versus guessing attempts might also be different, which may affect the encoding of the learning material. Furthermore, *pretesting* produces virtually all-incorrect responses, and this may affect learning comparing with a more balanced correct/error answer proportion.

Second, the *pretesting* paradigm does not allow for dissociating between the positive effects of error generation from the benefits of active learning, in which students dynamically interact with the study material (Bonwell & Eison, 1991). In the *pretesting* paradigm, the control condition (without pretesting) simply involves exposing learners to correct information (e.g., studying condition). This may be considered as passive learning as learners are not allowed to make an active response. Conversely, in the *pretesting* condition, learners are required to generate responses or guesses that reflect a dynamic and active learning process. In a similar vein, with the *pretesting* procedure, the control condition does not share the same *generation* and *testing* effects with the pretesting condition. And while a few studies have attempted to include active control conditions in *pretesting* (Potts & Shanks, 2014 ("Choice" condition); Seabrooke, et al., 2019a ("First Word" condition)), further research is needed to clarify this question.

In order to try to resolve these issues, alternative experimental or analysis procedures should be used. For example, including a prior study session before the initial test as in typical retrieval practice procedures. This could allow comparison of correct answers and genuine errors at the final test, and it equalizes active learning for both errors and correct answers. Thus, it is of considerable importance for further research to delve deeper into these problems and to obtain more precise knowledge about errorful learning.

Conclusion

Throughout this review, we have provided a theoretical framework in order to deepen our understanding of why experiencing errors can be advantageous for learning and to explore the scientific knowledge about how and when such errors can promote effective learning. In spite of the fact that considerable advances have been made on this topic, there are still some questions that remain unanswered and further empirical work is needed. And in this vein, it is important to consider the complex dynamics of the factors that modulate this type of learning, and to organize the empirical evidence taking into account the various explanatory theories.

This knowledge is especially important in the educational context, where traditionally there has been a tendency to avoid failure during learning. In fact, although teachers express openness towards students committing errors during learning, they usually do not provide many opportunities for students to deliberately engage with error commission (Pan et al., 2020). However, as shown in this review, including both successes and errors as learning opportunities could have positive consequences for learning. The present research emphasizes the notion that errors generated during learning are beneficial for later correct-recall. Despite this, it should be considered that if learners do make errors, the literature suggests that receiving corrective feedback is essential, which may not always occur (e.g., students may not see their incorrect responses and just receive numerical feedback, or they may obtain general feedback delivered to the whole class). And while the implementation of learning practices that allow errors could be a challenge in the classroom, errors should be embraced and valued as optimal sources of long-lasting learning. Thus, a more in-depth understanding of the advantages of experiencing errors could promote the idea that failure is an important part of constructive learning and that the active exploitation of mistakes is essential in education.

Funding This research was supported by a grant from the Basque Country Government (grant no. IT-1341-19) and from the Basque Country Government Department of Education (Predoctoral grant no. PRE-2020-1-0031).

Declaration

Conflicts interest The authors declare no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

References

Baddeley, A., & Wilson, B. A. (1994). When implicit learning fails: Amnesia and the problem of error elimination. *Neuropsychologia*, *32*(1), 53–68. https://doi.org/10.1016/0028-3932(94)90068-X

Bjork, E. L., & Bjork, R. A. (2014). Making Things Hard on Yourself, But in a Good Way: Creating Desirable Difficulties to Enhance Learning. In M. A. Gernsbacher & J. R. Pomerantz (Eds.), *Psychology and the real world: Essays illustrating fundamental contributions to society* (2nd ed., pp. 59–68). Worth.

Bonwell, C. C., & Eison, J. A. (1991). *Active Learning: Creating Excitement in the Classroom*. ASHE-ERIC Higher Education Reports.

Botvinick, M. M., Carter, C. S., Braver, T. S., Barch, D. M., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. https://doi.org/10.1037/0033-295X.108.3.624

Brod, G., Hasselhorn, M., & Bunge, S. A. (2018). When generating a prediction boosts learning: The element of surprise. *Learning and Instruction*, *55*(Educational Psychologist 31 2 1996), 22–31. https://doi.org/10.1016/j.learninstruc.2018.01.013

Butler, A. C., Karpicke, J. D., & Roediger, H. L. (2008). Correcting a Metacognitive Error: Feedback Increases Retention of Low-Confidence Correct Responses. *Journal of Experimental Psychology: Learning Memory and Cognition*, *34*(4), 918–928. https://doi.org/10.1037/0278-7393.34.4.918

Butterfield, B., & Metcalfe, J. (2001). Errors Committed with High Confidence Are Hypercorrected. *Journal of Experimental Psychology: Learning Memory and Cognition*, *27*(6), 1491–1494. https://doi.org/10.1037/0278-7393.27.6.1491

Butterfield, B., & Metcalfe, J. (2006). The correction of errors committed with high confidence. *Metacognition and Learning*, *1*, 69–84. https://doi.org/10.1007/s11409-006-6894-z

Carneiro, P., Lapa, A., & Finn, B. (2018). The effect of unsuccessful retrieval on children's subsequent learning. *Journal of Experimental Child Psychology*, *166*, 400–420. https://doi.org/10.1016/j.jecp.2017.09.010

Clare, L., & Jones, R. S. P. (2008). Errorless learning in the rehabilitation of memory impairment: A critical review. *Neuropsychology Review*, *18*(1), 1–23. https://doi.org/10.1007/s11065-008-9051-4

Clark, C. M. (2016). *When and Why does Learning Profit from the Introduction of Errors?* (Doctoral Dissertation, University of California Los Angeles). Retrieved August 8, 2020, from https://escholarship.org/uc/item/6zv5867p

Collins, A. M., & Loftus, E. F. (1975). A spreading-activation theory of semantic processing. *Psychological Review*, *82*(6), 407–428. https://doi.org/10.1037//0033-295X.82.6.407

Cyr, A. A., & Anderson, N. D. (2012). Trial-and-error learning improves source memory among young and older adults. *Psychology and Aging*, *27*(2), 429–439. https://doi.org/10.1037/a0025115

Cyr, A. A., & Anderson, N. D. (2015). Mistakes as stepping stones: Effects of errors on episodic memory among younger and older adults. *Journal of Experimental Psychology: Learning Memory and Cognition*, *41*(3), 841–850. https://doi.org/10.1037/xlm0000073

Cyr, A. A., & Anderson, N. D. (2018). Learning from your mistakes: does it matter if you're out in left foot, I mean field? *Memory*, *26*(9), 1281–1290. https://doi.org/10.1080/09658211.2018.1464189

Decker, A., Finn, A., & Duncan, K. (2020). Errors lead to transient impairments in memory formation. *Cognition*, *204*, 104338. https://doi.org/10.1016/j.cognition.2020.104338

Ebbinghaus, H. (1885). *Memory: A Contribution to Experimental Psychology*. Dunker.

Flavell, J. H., & Wellman, H. M. (1977). Metamemory. In R. V. Kail & J. W. Hagen (Eds.), *Perspectives on the development of memory and cognition*. Lawrence Erlbau.

Grimaldi, P. J., & Karpicke, J. D. (2012). When and why do retrieval attempts enhance subsequent encoding? *Memory and Cognition*, *40*(4), 505–513. https://doi.org/10.3758/s13421-011-0174-0

Guzmán-Muñoz, F. J. (2020). Effects of making errors in learning a foreign language. *Journal of Cognitive Psychology*, *32*(2), 229–241. https://doi.org/10.1080/20445911.2020.1711766

Hays, M. J., Kornell, N., & Bjork, R. A. (2013). When and why a failed test potentiates the effectiveness of subsequent study. *Journal of Experimental Psychology: Learning Memory and Cognition*, *39*(1), 290–296. https://doi.org/10.1037/a0028468

Houtman, F., & Notebaert, W. (2013). Blinded by an error. *Cognition*, *128*(2), 228–236. https://doi.org/10.1016/j.cognition.2013.04.003

Huelser, B. J., & Metcalfe, J. (2012). Making related errors facilitates learning, but learners do not know it. *Memory and Cognition*, *40*(4), 514–527. https://doi.org/10.3758/s13421-011-0167-z

Hunkin, N. M., Squires, E. J., Parkin, A. J., & Tidy, J. A. (1998). Are the benefits of errorless learning dependent on implicit memory? *Neuropsychologia*, *36*(1), 25–36. https://doi.org/10.1016/S0028-3932(97)00106-1

Iwaki, N., Matsushima, H., & Kodaira, K. (2013). Hypercorrection of High Confidence Errors in Lexical Representations. *Perceptual and Motor Skills*, *117*(1), 219–235. https://doi.org/10.2466/27.22.pms.117x13z7

Kang, S. H. K., Pashler, H., Cepeda, N. J., Rohrer, D., Carpenter, S. K., & Mozer, M. C. (2011). Does Incorrect Guessing Impair Fact Learning? *Journal of Educational Psychology*, *103*(1), 48–59. https://doi.org/10.1037/a0021977

Knight, J. B., Hunter Ball, B., Brewer, G. A., DeWitt, M. R., & Marsh, R. L. (2012). Testing unsuccessfully: A specification of the underlying mechanisms supporting its influence on retention. *Journal of Memory and Language*, *66*(4), 731–746. https://doi.org/10.1016/j.jml.2011.12.008

Kornell, N. (2014). Attempting to answer a meaningful question enhances subsequent learning even when feedback is delayed. *Journal of Experimental Psychology: Learning Memory and Cognition*, *40*(1), 106–114. https://doi.org/10.1037/a0033699

Kornell, N., Hays, M. J., & Bjork, R. A. (2009). Unsuccessful Retrieval Attempts Enhance Subsequent Learning. *Journal of Experimental Psychology: Learning Memory and Cognition*, *35*(4), 989–998. https://doi.org/10.1037/a0015729

Kornell, N., Klein, P. J., & Rawson, K. A. (2015). Retrieval attempts enhance learning, but retrieval success (versus failure) does not matter. *Journal of Experimental Psychology: Learning Memory and Cognition*, *41*(1), 283–294. https://doi.org/10.1037/a0037850

Landauer, T. K., & Dumais, S. T. (1997). A Solution to Plato's Problem: The Latent Semantic Analysis Theory of Acquisition, Induction, and Representation of Knowledge. *Psychological Review*, *104*(2), 211–240. https://doi.org/10.1037/0033-295X.104.2.211

Little, J. L., & Bjork, E. L. (2016). Multiple-choice pretesting potentiates learning of related information. *Memory and Cognition*, *44*(7), 1085–1101. https://doi.org/10.3758/s13421-016-0621-z

Melton, A. W., & Irwin, J. M. (1940). The Influence of Degree of Interpolated Learning on Retroactive Inhibition and the Overt Transfer of Specific Responses. *The American Journal of Psychology*, *53*(2), 173–203. https://doi.org/10.2307/1417415

Metcalfe, J. (2017). Learning from Errors. *Annual Review of Psychology*, *68*(1), 465–489. https://doi.org/10.1146/annurev-psych-010416-044022

Metcalfe, J., & Finn, B. (2012). Hypercorrection of high confidence errors in children. *Learning and Instruction*, *22*(4), 253–261. https://doi.org/10.1016/j.learninstruc.2011.10.004

Metcalfe, J., & Huelser, B. J. (2020). Learning from errors is attributable to episodic recollection rather than semantic mediation.

Neuropsychologia, *138*. https://doi.org/10.1016/j.neuropsychologia.2019.107296

Metcalfe, J., & Kornell, N. (2007). Principles of cognitive science in education: The effects of generation, errors, and feedback. *Psychonomic Bulletin and Review*, *14*(2), 225–229. https://doi.org/10.3758/BF03194056

Metcalfe, J., & Miele, D. B. (2014). Hypercorrection of high confidence errors: Prior testing bothenhances delayed performance and blocks the return of the errors. *Journal of Applied Research in Memory and Cognition*, *3*(3), 189–197. https://doi.org/10.1016/j.jarmac.2014.04.001

Metcalfe, J., & Shimamura, A. P. (Eds.). (1994). *Metacognition: Knowing about knowing.* The MIT Press.

Metcalfe, J., & Xu, J. (2018). Learning from one's own errors and those of others. *Psychonomic Bulletin and Review*, *25*(1), 402–408. https://doi.org/10.3758/s13423-017-1287-7

Metcalfe, J., Kornell, N., & Finn, B. (2009). Delayed versus immediate feedback in children's and adults' vocabulary learning. *Memory and Cognition*, *37*(8), 1077–1087. https://doi.org/10.3758/MC.37.8.1077

Metcalfe, J., Butterfield, B., Habeck, C., & Stern, Y. (2012). Neural Correlates of People's Hypercorrection of Their False Beliefs. *Journal of Cognitive Neuroscience*, *24*(7), 1571–1583. https://doi.org/10.1162/jocn_a_00228

Metcalfe, J., Casal-Roscum, L., Radin, A., & Friedman, D. (2015). On Teaching Old Dogs New Tricks. *Psychological Science*, *26*(12), 1833–1842. https://doi.org/10.1177/0956797615597912

Middleton, E. L., & Schwartz, M. F. (2012). Errorless learning in cognitive rehabilitation: A critical review. *Neuropsychological Rehabilitation*, *22*(2), 138–168. https://doi.org/10.1080/09602011.2011.639619

Mueller, M. M., Palkovic, C. M., & Maynard, C. S. (2007). Errorless learning: Review and practical application for teaching children with pervasive developmental disorders. *Psychology in the Schools*, *44*(7), 691–700. https://doi.org/10.1002/pits.20258

Murre, J. M. J., & Dros, J. (2015). Replication and Analysis of Ebbinghaus' Forgetting Curve. *PLOS ONE*, *10*(7), e0120644. https://doi.org/10.1371/journal.pone.0120644

Norman, D. A. (1981). Categorization of action slips. *Psychological Review*, *88*(1), 1–15. https://doi.org/10.1037/0033-295X.88.1.1

Notebaert, W., Houtman, F., Opstal, F. Van, Gevers, W., Fias, W., & Verguts, T. (2009). Post-error slowing: An orienting account. *Cognition*, *111*(2), 275–279. https://doi.org/10.1016/j.cognition.2009.02.002

Pan, S. C., Sana, F., Samani, J., Cooke, J., & Kim, J. A. (2020). Learning from errors: students' and instructors' practices, attitudes, and beliefs. *Memory*, *28*(9), 1105–1122. https://doi.org/10.1080/09658211.2020.1815790

Pashler, H., Cepeda, N. J., Wixted, J. T., & Rohrer, D. (2005). When Does Feedback Facilitate Learning of Words? *Journal of Experimental Psychology: Learning Memory and Cognition*, *31*(1), 3–8. https://doi.org/10.1111/j.1365-2648.2008.04878.x/abstract

Postman, L., & Underwood, B. J. (1973). Critical issues in interference theory. *Memory & Cognition*, *1*(1), 19–40. https://doi.org/10.3758/BF03198064

Potts, R., & Shanks, D. R. (2014). The benefit of generating errors during learning. *Journal of Experimental Psychology: General*, *143*(2), 644–667. https://doi.org/10.1037/a0033194

Potts, R., Davies, G., & Shanks, D. R. (2019). The benefit of generating errors during learning: What is the locus of the effect? *Journal of Experimental Psychology: Learning Memory and Cognition*, *45*(6), 1023–1041. https://doi.org/10.1037/xlm0000637

Pyc, M. A., & Rawson, K. A. (2010). Why testing improves memory: Mediator effectiveness hypothesis. *Science*, *330*(6002), 335. https://doi.org/10.1126/science.1191465

Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: variations in the effectiveness of reinforcement and nonreinforcement. In A. H. Black & W. F. Prokasy (Eds.), *Classical conditioning II: current research and theory* (pp. 64–99). Appleton-Century-Crofts.

Richland, L. E., Kornell, N., & Kao, L. S. (2009). The Pretesting Effect: Do Unsuccessful Retrieval Attempts Enhance Learning? *Journal of Experimental Psychology: Applied*, *15*(3), 243–257. https://doi.org/10.1037/a0016496

Roediger, H. L., & Karpicke, J. D. (2006). The Power of Testing Memory: Basic Research and Implications for Educational Practice. *Perspectives on Psychological Science*, *1*(3), 181–210. https://doi.org/10.1111/j.1745-6916.2006.00012.x

Seabrooke, T., Hollins, T. J., Kent, C., Wills, A. J., & Mitchell, C. J. (2019a). Learning from failure: Errorful generation improves memory for items, not associations. *Journal of Memory and Language*, *104*, 70–82. https://doi.org/10.1016/j.jml.2018.10.001

Seabrooke, T., Mitchell, C. J., Wills, A. J., Waters, J. L., & Hollins, T. J. (2019b). Selective effects of errorful generation on recognition memory: the role of motivation and surprise. *Memory*, *27*(9), 1250–1262. https://doi.org/10.1080/09658211.2019.1647247

Slamecka, N. J., & Fevreiski, J. (1983). The generation effect when generation fails. *Journal of Verbal Learning and Verbal Behavior*, *22*(2), 153–163. https://doi.org/10.1016/S0022-5371(83)90112-3

Slamecka, N. J., & Graf, P. (1978). The generation effect: Delineation of a phenomenon. *Journal of Experimental Psychology: Human Learning & Memory*, *4*(6), 592–604. https://doi.org/10.1037/0278-7393.4.6.592

Soraci, S. A., Franks, J. J., Bransford, J. D., Chechile, R. A., Belli, R. F., Carr, M., & Carlin, M. (1994). Incongruous Item Generation Effects: A Multiple-Cue Perspective. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*(1), 67–78. https://doi.org/10.1037/0278-7393.20.1.67

Soraci, S. A., Carlin, M. T., Chechile, R. A., Franks, J. J., Wills, T., & Watanabe, T. (1999). Encoding Variability and Cuing in Generative Processing. *Journal of Memory and Language*, *41*(4), 541–559. https://doi.org/10.1006/jmla.1999.2661

Squires, E. J., Hunkin, N. M., & Parkin, A. J. (1997). Errorless learning of novel associations in amnesia. *Neuropsychologia*, *35*(8), 1103–1111. https://doi.org/10.1016/S0028-3932(97)00039-0

Stevenson, H. W., & Stigler, J. W. (1994). *The learning gap: why our schools are failing and what we can learn from Japanese and Chinese education*. Simon & Schuster.

Tanaka, S., Miyatani, M., & Iwaki, N. (2019). Response format, not semantic activation, influences the failed retrieval effect. *Frontiers in Psychology*, *10*, 1–13. https://doi.org/10.3389/fpsyg.2019.00599

Tulis, M. (2013). Error management behavior in classrooms: Teachers' responses to student mistakes. *Teaching and Teacher Education*, *33*, 56–68. https://doi.org/10.1016/j.tate.2013.02.003

Tulving, E. (1972). Episodic and semantic memory. In E. Tulving & W. Donaldson (Eds.), *Organization of memory* (pp. 381–403). Academic Press.

van Loon, M. H., Dunlosky, J., van Gog, T., van Merriënboer, J. J. G., & de Bruin, A. B. H. (2015). Refutations in science texts lead to hypercorrection of misconceptions held with high confidence. *Contemporary Educational Psychology*, *42*, 39–48. https://doi.org/10.1016/j.cedpsych.2015.04.003

Vaughn, K. E., & Rawson, K. A. (2012). When is guessing incorrectly better than studying for enhancing memory? *Psychonomic Bulletin and Review*, *19*(5), 899–905. https://doi.org/10.3758/s13423-012-0276-0

Wahlheim, C. N., & Jacoby, L. L. (2013). Remembering change: The critical role of recursive remindings in proactive effects of memory. *Memory and Cognition*, *41*(1), 1–15. https://doi.org/10.3758/s13421-012-0246-9

Wong, S. S. H., & Lim, S. W. H. (2019). Prevention–Permission–Promotion: A Review of Approaches to Errors in Learning. *Educational Psychologist*, *54*(1), 1–19. https://doi.org/10.1080/00461520.2018.1501693

Yang, C., Potts, R., & Shanks, D. R. (2017). Metacognitive unawareness of the errorful generation benefit and its effects on self-regulated learning. *Journal of Experimental Psychology: Learning Memory and Cognition*, *43*(7), 1073–1092. https://doi.org/10.1037/xlm0000363

Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The neural basis of error detection: Conflict monitoring and the error-related negativity. *Psychological Review*, *111*, 931–959. https://doi.org/10.1037/0033-295X.111.4.931

Zawadzka, K., & Hanczakowski, M. (2019). Two routes to memory benefits of guessing. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *45*(10), 1748–1760. https://doi.org/10.1037/xlm0000676