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Prevention–Permission–Promotion: A Review of Approaches to Errors in Learning

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Errors are often perceived as undesirable events to be avoided at all costs. However, a growing body of research suggests that making errors is, in fact, beneficial for learning. Building on human resource development literature, the present review proposes a 3P framework of approaches to errors during learning: prevention (avoiding or observing errors), permission (allowing errors), and promotion (inducing or guiding errors). This framework is applied to examine and integrate the empirical evidence on errors that have been commonly investigated in cognitive, educational, and applied psychology research. The psychological mechanisms of each error approach are discussed, and implications for education are considered. This review then concludes by highlighting the ways in which the various error approaches interact with learner characteristics and learning contexts, as well as discussing the role of feedback in error correction and proposing directions for future research toward understanding how errors can be optimized in learning.

To err is human. Indeed, human history is replete with errors, ranging from Einstein’s removal of the cosmological constant from his general theory of relativity and thus missing out on predicting the accelerating expansion of the universe to 12 publishers’ rejection of a manuscript that would later become the first book in the best-selling *Harry Potter* series by J. K. Rowling. Given that errors are often costly, it is unsurprising that they traditionally have a poor reputation and are typically viewed as undesirable events to be avoided. However, a growing body of research in cognitive and educational psychology has established that errors in low-stakes contexts enhance learning when they are followed by corrective feedback (see Metcalfe, 2017, for a recent review), in line with the familiar adage that “we learn from our mistakes.” Because errors are inextricable from the human condition and are “necessary and in themselves fruitful steps in a learning process” (Wide, 2009, p. 584), it may be worthwhile to embrace them and consider how we can best benefit from them.

How are errors approached in learning, and how can they be optimized to enhance learning? Here, errors are

considered as objective outcomes that involve incorrect responses (i.e., deviations from correct responses). The present article (a) proposes a framework of approaches to errors in learning; (b) applies this framework to review and integrate the empirical evidence on errors in cognitive, educational, and applied psychology literature; (c) examines the underlying psychological mechanisms of the various error approaches; (d) discusses their implications for education; (e) highlights the ways in which these error approaches interact with learner characteristics and learning contexts; (f) discusses the role of feedback in error correction; and (g) concludes by suggesting directions for future research.

A 3P FRAMEWORK: PREVENTION, PERMISSION, PROMOTION

Drawing on and extending human resource development research that has advanced a typology of approaches to error occurrence during workplace training (Lorenzet, Salas, & Tannenbaum, 2005), this review proposes a Prevention–Permission–Promotion (3P) framework of approaches to errors during learning, with each approach adopting an increasingly active and positive stance toward errors that are generated by learners (see Figure 1). First, under the error prevention approach, active errors in

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3P FRAMEWORK OF APPROACHES TO ERRORS		
PREVENTION Learners <i>avoid</i> making errors of their own or <i>observe</i> others' errors	PERMISSION Learners passively <i>allow</i> errors to occur naturalistically	PROMOTION Learners are actively <i>induced</i> or <i>guided</i> to make errors

FIGURE 1 The Prevention–Permission–Promotion (3P) framework of approaches to errors during learning.

learning are eliminated by preventing learners from personally committing errors, whereby errors can be *avoided* (learners are not exposed to errors at all; errorless learning) or *observed* (learners are exposed to others' errors and are thus prevented from making errors of their own). Second, under the error permission approach, errors are passively *allowed* to occur (learners are not prevented from making errors, which may then arise naturalistically). Third, under the error promotion approach, learners' errors are actively elicited, whereby such errors may be *induced* (challenge is added to the learning task to evoke errors on learners' part) or even *guided* (learners are led into making specific errors in a structured manner).¹

In the following sections of this review, the 3P framework is applied to categorize and examine the errors in learning that have commonly been interrogated in cognitive and educational psychology studies, compared to workplace training research. Representative studies that illuminate each error approach are discussed.

Error Prevention

Error prevention is characterized by preventing learners from making errors themselves, and includes *avoiding* and *observing* errors—whereas the former eliminates all exposure to errors in learning, the latter removes the need for learners to make errors of their own by exposing them to others' errors.

¹The terms *prevention* and *promotion* have also been commonly used in self-regulatory theories (e.g., Higgins, 1997, 1998). There are some similarities in the ways we apply these terms in our 3P framework of approaches to errors. For example, to the extent that one considers errors to be aversive events, a parallel between error prevention and a prevention self-regulatory focus is that both are concerned with the absence and presence of negative outcomes by insuring correct rejections and avoiding errors of commission (e.g., Higgins, 1997). However, there are also some important differences between a prevention/promotion focus in self-regulation versus the approaches to errors discussed in this review. For example, whereas a promotion self-regulatory focus relates to a sensitivity to positive outcomes via insuring hits and avoiding errors of omission (Higgins, 1997), the approach of error promotion involves actively evoking or even insuring errors. As such, it is noteworthy that the approaches of error prevention and promotion are not entirely identical to a prevention focus and promotion focus in self-regulation.

Avoiding Errors

Avoiding errors commonly involves imposing learning conditions that leave little room for errors to be committed. In some instances, learners may even be explicitly instructed to avoid errors at all costs as these presumably inhibit learning (e.g., Chillarege, Nordstrom, & Williams, 2003; Gully, Payne, Koles, & Whiteman, 2002; Nordstrom, Wendland, & Williams, 1998). Historically, the error avoidance approach has been championed by advocates such as Skinner (1958, 1968), who notably contended that learners should strive for errorless performance, aided by the use of “teaching machines” or programs that shape the required behavior through a gradual progression with as few errors as possible (see also Ausubel, 1968; Bandura, 1986; Terrace, 1963).

In cognitive psychology studies, the error avoidance approach is typically exemplified by a read-only condition, in which participants are exposed only to correct information and target stimuli such as word pair associates, foreign vocabulary, or factual information during studying and are not permitted any opportunities for responding incorrectly (if at all), before they are subsequently tested on their learning (e.g., Grimaldi & Karpicke, 2012; Huelser & Metcalfe, 2012; Kornell, Hays, & Bjork, 2009; Potts & Shanks, 2014). In contrast, error-avoidant training in workplace research has often focused on preventing procedural errors during software training (e.g., Frese et al., 1991) or driving simulations (e.g., Ivancic & Hesketh, 2000). When slips occur (e.g., trainees accidentally mistype a command in spite of detailed “click-by-click” instructions given), trainers immediately intervene to correct these errors, such that trainees undergo a learning experience that is largely error reducing.

Likewise, the approach of avoiding errors in educational contexts has been embodied by the use of worked examples, in which learners are presented with a problem and its correct solution in a detailed, step-by-step manner to be studied and emulated when solving other similar problems, such that errors are reduced or eliminated during learning (e.g., Renkl, 1997, 2002; Sweller & Cooper, 1985; Ward & Sweller, 1990; for a review, see Atkinson, Derry, Renkl, & Wortham, 2000). As compared to unassisted discovery in which learners independently explore and work out the solutions without any guidance (discussed later under the approach of allowing errors), studying worked examples has generally been shown to produce superior learning for novices (Kirschner, Sweller, & Clark, 2006). For instance, Sweller and Cooper (1985) found that the use of worked examples in learning algebra not only consumed less problem-solving time during initial skill acquisition as compared to conventional (unguided) problems, but also led to faster performance

with fewer errors when learners were subsequently asked to solve test problems that were structurally similar to the initial ones.

Psychological mechanisms of avoiding errors. Proponents of error-avoidant learning have suggested that inefficient approaches and solutions are practiced when learners err, such that learning is inhibited when incorrect responses are strengthened and must subsequently be overridden before correct solutions can be learned (e.g., Ausubel, 1968). Indeed, errors can be costly for subsequent performance—in a phenomenon known as post-error slowing (PES), people tend to slow down after making an error (Rabbitt, 1966; Rabbitt & Rodgers, 1977). Of interest, although the dominant assumption in PES literature has been that slowing down after an error serves the adaptive function of increasing response caution to improve post-error accuracy (see Dutilh et al., 2012, for a review), recent neuroscientific evidence instead suggests that PES results from an interaction between two opposing neural processes—an increased decision threshold whereby more evidence must be accumulated before the decision is made, and reduced sensitivity to incoming sensory information due to the diversion of attention after making an error—such that people do not necessarily become more accurate after erring (Purcell & Kiani, 2016; see also Notebaert et al., 2009). Consistent with the notion that individuals do not always learn from their past mistakes, errors of omission during tip-of-the-tongue states tend to be repeated even after corrective feedback has been given (Warriner & Humphreys, 2008), and errors of commission may be repeated after a 1-week delay when learners forget the correct answers that had initially been provided during feedback (Butler, Fazio, & Marsh, 2011).

To explain these findings, one potential account is that the very act of erring constitutes implicit learning and practicing of that error even if corrective feedback is later given. Thus, one's mental pathways to the error are strengthened with more time spent on it, thereby increasing the likelihood that this same error will be repeated in the future, much like "spinning one's tyres in the snow, resulting in nothing more than the creation of a deeper rut" (Warriner & Humphreys, 2008, p. 540). Indeed, Baddeley and Wilson (1994; see also Page, Wilson, Shiel, Carter, & Norris, 2006) have proposed that the benefits of errorless learning over trial-and-error learning can be attributed to the role of implicit memory, which does not involve conscious recollection of information and is presumably unable to eliminate errors but simply emits the dominant response (cf. Hunkin, Squires, Parkin, & Tidy, 1998; Tailby & Haslam, 2003).

At the same time, given the limitations of working memory capacity, avoiding errors may facilitate learning by reducing extraneous (unnecessary) cognitive load.

According to cognitive load theory (Sweller, 1988; Sweller, van Merriënboer, & Paas, 1998), complex learning tasks such as problem solving often impose heavy cognitive load on learners, especially when novices engage in strategies that are irrelevant to learning and are overwhelmed by numerous interacting elements that they must simultaneously process. As such, by avoiding errors through providing learners with worked examples that focus their attention on studying relevant solutions and acquiring domain-specific schemas, cognitive load may be optimized to enhance learning. In support of this notion, worked examples that lower cognitive load by reducing learners' need to mentally integrate multiple information elements during problem solving have been found to produce superior test performance, as compared to unguided problems and worked examples that require learners to split their attention between multiple sources of information (Ward & Sweller, 1990). Hence, rather than the use of worked examples, per se, one critical factor underlying the effectiveness of avoiding errors appears to be the extent to which this approach reduces extraneous cognitive load so that learners may direct their cognitive resources to relevant solution strategies that support schema acquisition and meaningful learning.

Educational implications of avoiding errors. In a review of errorless learning procedural variations, Mueller, Palkovic, and Maynard (2007) identified various techniques that can be employed in school settings to teach new discriminations (i.e., responding differently to various stimuli) to young children with pervasive developmental disorders, such as gradually changing known stimuli to the terminal, initially unknown choices, and physically blocking learners from selecting the incorrect response. Such errorless learning techniques may be more effective when they involve active encoding strategies (e.g., Tailby & Haslam, 2003). Accordingly, in educational contexts, teachers may consider providing prompts to their students that elicit correct responses while involving more active processing, as opposed to simply "spoon-feeding" the correct answers to their students.

When introducing new concepts to students, teachers may also provide worked examples that reduce cognitive load and errors during problem solving, given that these have been found to benefit novice learners not only in laboratory settings, but also in classroom instruction (e.g., Ward & Sweller, 1990; Zhu & Simon, 1987). The efficacy of worked examples can potentially be augmented by incorporating interactive elements that induce processes that are directly relevant for learning (for a review, see Atkinson & Renkl, 2007). In computer-based learning environments, for instance, animated pedagogical agents that use nonverbal feedback such as gaze and gesture can be employed to better direct learners' attention to the

relevant material and foster learning (Atkinson, 2002). In addition, instructional explanations of the worked examples can be made available upon learners' request to facilitate understanding (Renkl, 2002). However, like the use of prompts to promote active encoding strategies, encouraging active processing of the relevant material in worked examples may be more effective than providing passive direct instruction (for a meta-analytic review, see Wittwer & Renkl, 2010). For instance, learners can be prompted to actively explain the worked examples to themselves (e.g., Atkinson & Renkl, 2007), or worked-out solution steps can be gradually faded out by systematically omitting steps and introducing gaps that learners are meant to fill in (e.g., Renkl, Atkinson, Maier, & Staley, 2002; for a discussion, see Renkl & Atkinson, 2003). When both of these techniques are combined, better transfer of learning may ensue (Atkinson, Renkl, & Merrill, 2003).

However, there are several drawbacks of avoiding errors. For instance, as the error avoidance approach is typically dependent on prompts or the correct answer being supplied, it may inhibit active exploration that facilitates the development of new knowledge (e.g., Dormann & Frese, 1994). The benefits of avoiding errors also appear to be limited to novice learners and relatively less complex learning tasks. That is, although novices without prior domain knowledge may benefit from avoiding errors through worked examples, processing such worked examples is redundant for more experienced learners who experience fewer to no benefits from doing so (e.g., Kalyuga, Chandler, Tuovinen, & Sweller, 2001; Tuovinen & Sweller, 1999). In addition, although avoiding errors has been found to aid the learning of relatively simple responses such as discriminating between two options in animal studies (e.g., Terrace, 1963), the applicability of this advantage to more complex educational contexts with human learners remains uncertain, given that principles related to the learning of simple skills may not necessarily generalize to more complex skills (Wulf & Shea, 2002). In particular, higher order thinking often involves applying, synthesizing, and evaluating knowledge (Bloom, 1956). Yet there is a lack of evidence that avoiding errors benefits such higher order learning outcomes, especially when new responses are required or new situations are involved. That is, there is limited support for any benefits of error avoidance in facilitating transfer of learning to novel contexts (e.g., Jones & Eayrs, 1992). Moreover, in complex domains of human learning, errors are almost inevitable. Learning how to do scientific research, for instance, is often fraught with difficulties and problems that students must learn to navigate, sometimes unsuccessfully, while confronting their "absolute stupidity" and realizing that their "ignorance is infinite" (M. A. Schwartz, 2008, p. 1771). As such, the extent to which

errors can and should be reasonably avoided altogether in complex learning contexts and across the trajectory of expertise development is questionable.

Furthermore, error avoidance may negatively impact academic risk taking, which Clifford (1991) defined as students' selection of academic tasks that vary in their probability of success owing to their varying levels of difficulty and are accompanied by (expected) feedback (see also Tan, Lim, & Manalo, 2016). Under the error avoidance approach, learners may avoid selecting more difficult tasks because these increase the likelihood of one making errors. In particular, error avoidance (especially if learners are explicitly instructed to avoid errors at all costs) is associated with a prevention self-regulatory focus that is concerned with safety and security through achieving non-negative outcomes, as opposed to a promotion self-regulatory focus that is oriented toward accomplishments and aspirations through achieving positive outcomes (Higgins, 1997, 1998). Because one's inclination under a prevention focus is to be vigilant against errors and insure against producing them, learners with this self-regulatory focus display lower persistence when confronted with difficult tasks (e.g., Crowe & Higgins, 1997). Yet, academic risk taking has been associated with social, motivational, and cognitive benefits, including greater self-efficacy (Bandura, 1977), "flow" states characterized by intense task immersion and enjoyment (Csikszentmihalyi, 1990), and even optimal cognitive development (Vygotsky, 1978). Consequently, avoiding errors and risks may lead one to miss out on the value of healthy and optimal challenge.

Indeed, even for memory-impaired patients, errorless learning may yield poorer long-term gains than errorful learning that encourages difficult (and thus error-prone) retrieval practice, which has been associated with more robust learning (for a review, see Middleton & Schwartz, 2012). Thus, error-avoidant learning may not always be ideal, given that it often fails to harness the potential of personally initiated and directed elaborative processes that may be particularly beneficial for learning (N. D. Anderson & Craik, 2006). Even though learners can be provided with opportunities to actively generate correct answers with the aid of prompts during errorless learning (e.g., Tailby & Haslam, 2003), overreliance on these prompts may hamper learning when they are removed (Jones & Eayrs, 1992). Hence, although errors can be costly, perhaps the costs to be borne are even greater when learners do not maximize their gains from adopting more active learning strategies that effectively manage errors, which invariably arise during the naturalistic acquisition of knowledge.

Notably, R. A. Bjork (1994) highlighted the advantages of implementing "desirable difficulties" in learning—although some conditions of learning may appear to cause difficulties for learners and slow down knowledge acquisition, they may actually produce improved learning

outcomes in the long run. Accordingly, although errors may slow down performance (i.e., PES), their absence may in fact signal that learners are not optimally exposing themselves to desirable difficulties that ultimately facilitate durable learning (e.g., R. A. Bjork, 1994; Clark & Bjork, 2014). Hence, another type of error prevention involves learners observing others' errors without being compelled to make errors of their own.

Observing Errors

Learning can occur not only through direct firsthand experience but also through observing others. Although errors are typically self-generated, observing errors involves exposing individuals to others' errors (vicarious errors; e.g., Ivancic & Hesketh, 2000; Joung, Hesketh, & Neal, 2006). This technique has been shown to offer some benefits in discrimination learning that involves reproducing responses similar to those observed (e.g., Templeton, 1998). When transfer of learning to similar but nonidentical tasks is required, trainees may also profit more from a combination of observing others' errors and correct responses in behavior modeling training, as opposed to only observing others' correct responses (e.g., Baldwin, 1992; see Taylor, Russ-Eft, & Chan, 2005, for a meta-analytic review).

As compared to workplace training research, cognitive psychology studies have devoted relatively little attention to examining the effects of observing others' errors. Although some studies have made a distinction between self- and other-generated errors (see Metcalfe, 2017, for a review), most evidence of the effects of learning from others' errors has been indirect (e.g., Jacoby, Craik, & Begg, 1979). In one notable exception that more directly tested the effects of observing other-generated errors versus committing errors oneself, Metcalfe and Xu (2018) employed a multiple-person Skype setup and compared a "Call-on" condition in which participants were designated to answer a question before it was asked, a "Hook" condition in which the question was first posed generally before the person designated to answer it was specified, and a "Listen" condition in which the experimenter read both the question and correct answer. As all corrective feedback was provided by the experimenter, the critical manipulation related to whether participants heard their own errors being corrected after having made them or heard another person's errors being corrected. Metcalfe and Xu (2018) found that performance on a delayed memory assessment benefited from self- than other-generated errors of commission but not omission, whereby participants were more likely to recall the correct answer to a question if they had personally committed an error on this question during learning, as opposed to merely witnessing another learner responding incorrectly.

Similar trends have also been observed in educational psychology research on peer grading, in which learners are incidentally exposed to their peers' errors when correcting their work. For instance, Sadler and Good (2006) found that students who graded their peers' tests did not display better performance on a second, unannounced administration of the same test a week later, as compared to students who did not grade any tests at all. In contrast, students who graded their own initial tests performed significantly better when they later completed the same test again. Thus, observing and correcting others' errors seems to pale in comparison to making and correcting one's own errors (self-generated errors are later discussed under the approach of allowing errors), although observing others' incorrect, rather than correct, responses may remain relatively more useful for learning (e.g., Joung et al., 2006; Templeton, 1998).

Psychological mechanisms of observing errors.

Why might witnessing others' errors rather than correct responses aid an observer's learning? In tasks that involve discrimination, first learning what *not* to do may be relatively more important than learning what to do (e.g., Biederman, 1967; Mason, Stevens, Wixon, & Owens, 1980; Templeton, 1998). Observing others' errors may also prompt learners to identify problems and critically analyze a given situation or existing ineffective solutions, thus increasing one's awareness of incorrect responses that should be avoided so that desired strategies can be implemented (e.g., Joung et al., 2006). Given that exposure to others' correct responses alone does not necessarily reduce learners' ineffective behaviors (Baldwin, 1992), observing errors may enrich learners' mental models of behavior strategies that they can adopt in various contexts.

Educational implications of observing errors.

As a whole, extant literature suggests that observing others' errors can be beneficial for learning, relative to witnessing others' correct responses only. At worst, observing errors is typically not harmful in classroom contexts when learners are exposed to their classmates' errors, as opposed to hearing their correct responses alone (e.g., Metcalfe & Xu, 2018). Similar to avoiding errors, observing others' errors circumvents the potential negative emotional consequences of committing errors oneself. Yet, observing others' errors additionally allows for the possibility of systematic exposure to and feedback from selected errors, whereby individuals can learn about the consequences of these errors in a nonthreatening environment (e.g., Joung et al., 2006).

Accordingly, observed errors can be viably introduced in educational settings to support learning, particularly when stimulus discrimination or transfer of correct

behaviors, skills, and responses to novel contexts is the desired primary learning objective (e.g., Baldwin, 1992). For instance, students may be instructed to first complete preclass activities to acquire relevant knowledge, before playing a game of observing and identifying their teachers' (intentional) conceptual errors during class time based on the assigned preparatory content, with discussion and feedback built into the game session.

However, although students can potentially learn from others' errors without the need for firsthand erring, perhaps the full benefits of learning from errors may be gleaned only through actively committing and correcting one's own errors (e.g., Metcalfe & Xu, 2018). Although observing errors creates a "safe distance" such that other-generated errors may be perceived as less personally threatening, this may also reduce one's active engagement with errors that may be essential for deep learning (DaRosa & Pugh, 2012). The following sections of this review thus explore approaches in which errors are made by learners themselves.

Error Permission

Under the approach of error permission, errors are *allowed* to arise in naturalistic ways when learners are not prevented from making errors during exploratory or trial-and-error activities.

Allowing Errors

Allowing errors involves a passive or chance use of errors, whereby learners may make incidental errors during exploration but the nature and frequency of these errors cannot be anticipated since no measures are taken to actively evoke specific errors (Lorenzet et al., 2005). In human resource development research, exploratory training methods allow for errors to be made when trainees are given minimal instructions on how to solve a task and are encouraged to actively explore their learning environment through self-directed strategies such as trial-and-error (e.g., Gully et al., 2002; Keith, Richter, & Naumann, 2010).

Such exploratory learning processes that allow for errors to occur have also been studied in cognitive psychology research. In what has been termed the *generation effect*, information that learners actively produce themselves is remembered better than information presented by an external source (Jacoby, 1978; Slamecka & Graf, 1978; see Bertsch, Pesta, Wiscott, & McDaniel, 2007, for a meta-analytic review). Although most early studies of the generation effect examined learners' generation of correct responses, recent studies have begun to investigate the effects of generating incorrect responses. Notably, Metcalfe and Xu (2018) have found that making

"naturalistic" errors of commission aids memory—learners' recall of the correct answer is enhanced when they inadvertently generate incorrect responses to general information questions and are given corrective feedback, as opposed to simply hearing another person's incorrect responses. Thus, the advantages of generation are not constrained to correctly generated items. Rather, generating errors can also be helpful for learning.

Psychological mechanisms of allowing errors.

The finding that making errors benefits learning is, perhaps, counterintuitive as one might expect that competing incorrect responses would interfere with and inhibit learning of correct responses. However, some researchers have suggested that errors may in fact serve as useful retrieval cues on future recall attempts, given that concepts activated during error generation may create a distinctive context or alternative pathways to the correct response (e.g., Kornell et al., 2009; Potts & Shanks, 2014).

At the same time, generating errors may enhance memory by potentiating the encoding of subsequent corrective feedback (e.g., Kornell et al., 2009; Potts & Shanks, 2014), especially when an existing cue–target association has been suppressed due to the error, such that later relearning attempts involving that association become more potent (e.g., Hays, Kornell, & Bjork, 2013). In particular, learners may pay more attention to corrective feedback following error generation due to their aroused curiosity to know the correct answer after having actively made the effort to derive it, albeit unsuccessfully (Potts & Shanks, 2014). Notably, Rescorla and Wagner's (1972) model of classical conditioning postulates that the amount of learning that takes place is a positive function of the magnitude of surprise triggered by a mismatch between an event and one's expectations. Accordingly, by generating surprise when learners' expectations are violated upon discovering that they have responded incorrectly, errors (particularly those made with high confidence) may increase attention to and encoding of subsequent corrective feedback, thereby improving learning (e.g., Fazio & Marsh, 2009). Indeed, as compared to correct responses, errors elicit increased defensive startle reflexes that are predicted by heightened error-related negativity—an event-related potential in the brain after error commission (Hajcak & Foti, 2008). In turn, the magnitude of such error-related neural activity, as well as that of brain responses related to the presentation of corrective feedback, positively predicts future correction and learning when the same stimuli that had initially led to errors are encountered again (e.g., Hester, Madeley, Murphy, & Mattingley, 2009; van der Helden, Boksem, & Blom, 2010). Similarly, the delta rule in McClelland and Rumelhart's (1985) connectionist model posits that learning is driven by the differences in activation between

actual and desired states (i.e., errors) in a neural network, which are then used to adjust the strength of the network's connections and reduce the magnitude of these errors for learning to occur. In these ways, errors may catalyze learning processes.

To reap the advantages of allowing errors, however, it appears vital that learners overtly produce these errors themselves. Of interest, Metcalfe and Xu (2018) found that even if participants covertly generated an incorrect response to a question with the expectation that they may be called upon to respond but in which another learner was asked to answer aloud, any memory benefit observed was weak at best and did not persist on a delayed test. Similarly, choosing an incorrect response during studying has been found to be just as (in)effective as merely reading the correct response, and does not offer the same memory benefit as actively generating an error (Potts & Shanks, 2014).

One potential account for these effects is that generating errors may demand relatively greater active engagement that taps into learners' own mental models, as compared to choosing incorrect responses or hearing another person's errors (Metcalfe, 2017; Potts & Shanks, 2014). The increased cognitive engagement from producing errors may then strengthen existing associations and potentiate subsequent feedback more effectively while fostering self-regulatory processes that facilitate learning, such as metacognitive activities when monitoring one's progress (e.g., Bell & Kozlowski, 2008; Keith & Frese, 2005; Keith et al., 2010; Wang, Zhang, & Salvendy, 2010).

Yet, mental effort and engagement alone may be insufficient to account for the learning advantages of generating errors, in view of Bertsch et al.'s (2007) observations in their meta-analytic review that studies with easy (e.g., switching two underlined letters in a word), moderate (e.g., word fragment completions), and hard (e.g., mental multiplication to derive a target number) generation tasks yielded similar effect sizes. Testing the underlying mechanisms of this effect is thus an important challenge for future empirical work to address, in order to gain insight on when and why error generation enhances learning.

Educational implications of allowing errors. In educational contexts, allowing errors is exemplified by discovery learning (also referred to as problem-based learning, inquiry learning, and experiential learning; see Kirschner et al., 2006). Although a consistent definition of "discovery learning" has yet to be agreed upon even after decades of research (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011; Klahr & Nigam, 2004), this method broadly involves allowing learners to independently discover and gain a conceptual understanding of the target

information with little or no guidance (Bruner, 1961; see Alfieri et al., 2011, for a meta-analytic review).

Although proponents of discovery learning have suggested that the exploration process is essential for learners to develop inquiry skills as active agents in constructing their knowledge (e.g., Bruner, 1961), other researchers have questioned the efficacy of unstructured exploration (e.g., Kirschner et al., 2006; Klahr & Nigam, 2004; Mayer, 2004). Rather, the effectiveness of allowing errors may partially hinge on the extent to which discovery is guided (e.g., through feedback, scaffolding, or elicited self-explanation). Notably, in their meta-analytic review of 164 studies, Alfieri et al. (2011) found that explicit instruction was superior to unassisted discovery learning under most conditions, but that enhanced (guided/assisted) discovery led to greater learning than other comparison methods of instruction such as direct teaching and providing worked examples. Presumably, unstructured exploration in complex environments imposes a relatively heavy cognitive load that impedes learning, especially for novice learners who may not possess the relevant schemas to independently integrate new information with their prior knowledge (Kirschner et al., 2006). As Bruner (1961) suggested, "Discovery, like surprise, favours the well-prepared mind" (p. 22).

As such, it may be crucial for teachers to scaffold their students' commission of errors to prevent unproductive floundering when students are left without any guidance (for a review, see Kapur, 2016). For instance, teachers can provide guiding questions when their students actively explore problem solutions and can offer corrective feedback and worked examples after their students have generated incorrect responses. To support students' learning when errors arise in e-learning contexts (for a discussion, see Priem, 2010), technological aids can also be enlisted. For example, intelligent tutoring systems can facilitate error detection and correction by pointing out learners' errors when they are committed, before guiding learners to identify their incorrect actions and the specific situation features associated with these errors, and supporting their revision of faulty knowledge structures and overly general rules (e.g., Mathan & Koedinger, 2005; for a discussion, see Ohlsson, 1996). In the absence of such intelligent systems, however, a potential drawback of allowing errors through exploration is that it may be difficult for educators to provide systematic feedback because learners' specific errors cannot be anticipated. In response to this challenge, the approach of error promotion may be considered.

Error Promotion

The error promotion approach of actively eliciting errors from learners encompasses *inducing* or *guiding* errors—

whereas the former is characterized by creating challenging learning conditions designed to evoke learners' errors, the latter involves leading learners into making specific errors.

Inducing Errors

Unlike errors that are allowed to occur but are not actively evoked by teachers or trainers, inducing errors involves more intentionality in purposefully adding challenge to the learning task to elicit errors on the part of learners (Lorenzet et al., 2005). In human resource training research, this is commonly achieved through increasing the complexity of the task at hand or withholding information needed to solve it (e.g., Dormann & Frese, 1994; Frese et al., 1991; Nordstrom et al., 1998), often while framing errors positively. In particular, error management training (EMT) involves both active exploration with minimal guidance and explicit encouragement of errors through positive statements such as "The more errors you make, the more you learn!" (e.g., Frese & Altmann, 1989; Keith & Frese, 2005). Such error management instructions are meant to develop error-tolerant attitudes in learners by emphasizing that errors are expected as part of the learning experience and that they may provide positive informational feedback (e.g., Ivancic & Hesketh, 1995/1996; see also Dormann & Frese, 1994).

In cognitive and educational psychology research, errors are typically induced by having learners make guesses during trial-and-error learning. For example, patients with amnesia in Baddeley and Wilson's (1994) study were asked to guess a five-letter target word (e.g., *quote*) given its first two letters (e.g., *QU*). If participants' first guess was the original target word, then the target was substituted with a backup word to artificially ensure that at least one error had been made. Likewise, Cyr and Anderson (2015) had participants generate either conceptual guesses (e.g., guessing the target word *mango* when prompted with the category *a fruit*) or lexical guesses (e.g., guessing the target word *strawberry* when shown the word stem *st_____*). To ensure error commission, words that participants had not guessed were always selected as the "correct" targets. Both studies' findings have converged to reveal that error generation in lexical guesses leads to poorer recall performance than errorless learning in which participants are simply presented with the cue-target pair without being required to guess. Crucially, however, Cyr and Anderson further found that induced conceptual guesses increased recall performance relative to errorless learning, indicating that the nature of one's errors may influence the extent to which learning benefits are derived.

In other variations of trial-and-error learning, errors are actively evoked by having learners guess the answers to

questions designed to render success impossible (or at least, highly unlikely), such as fictional trivia questions with no real answers to begin with, or targets that are weak associates of their cues (e.g., Grimaldi & Karpicke, 2012; Huelser & Metcalfe, 2012; Kornell et al., 2009). Such studies have shown that incorrect guesses can promote learning if the errors induced are related to the cue or question at hand, consistent with the finding that conceptual guesses enhance learning (e.g., Cyr & Anderson, 2015).

However, some researchers have highlighted the importance of differentiating between learners' incorrect responses that are genuine errors versus failures to guess the experimenter's intended "correct answer" at the time (e.g., Metcalfe, 2017; Potts & Shanks, 2014). Notably, in a more direct test of the causal relationship between forced incorrect guessing and recall performance, Kang et al. (2011) presented participants with obscure facts that each had a corresponding question (e.g., "Where is Disko Island?") and correct answer (e.g., "Greenland"). When participants reported that they "had no idea" of the answer to a question, the computer program insisted upon a guess in half of these instances before immediate corrective feedback was presented. Participants' forced guesses were very rarely correct, suggesting that they genuinely did not know the answers. Kang et al. found that on a final test given 1 day later, there were no significant differences between participants' recall of items that they had erroneously guessed the answers to versus items that had not required a guess. That is, incorrect guessing even when participants were highly unsure did not affect or impair their learning relative to leaving these answers blank, suggesting that errors of commission versus omission do not differentially affect learning. This stands in contrast to the benefits of incorrect guesses (i.e., commission errors) over errorless learning (e.g., direct presentation of the correct answers without guessing) observed in the studies described earlier (e.g., Cyr & Anderson, 2015; Kornell et al., 2009).

At the same time, Potts and Shanks (2014) tested the effects of "errorful generation" when learners make invariably incorrect guesses because the test material is entirely new to them, such that the errors made are unlikely to be semantically related to either cues or targets. In their study, participants learned novel (unfamiliar) stimuli such as obscure English words and their definitions (e.g., *valinch—tube*). Potts and Shanks found that generating incorrect guesses followed by feedback led to better memory for the correct targets than reading the cue-target pairs or choosing incorrectly from given options. Although this result may appear inconsistent with research demonstrating that the advantages of errorful learning are a function of semantic relatedness (e.g., Huelser & Metcalfe, 2012), it may be that the errors in

Potts and Shanks' study engaged learners in conceptual thinking (e.g., guessing *ruler* because the target word *valinch* contains the word *inch*) and thus led to corresponding learning benefits (Cyr & Anderson, 2015).

Besides enhancing memory recall, induced errors have been found to facilitate higher order learning outcomes such as transfer of learning in problem solving. For instance, in a study by Gick and McGarry (1992), learners were presented with a challenging source problem before undergoing one of three conditions, in which they were asked to (a) try solving the problem (invariably producing persistent failures; inducing errors) before being provided with the solution, (b) read and copy the problem with two failed solutions (i.e., exposure to other-generated errors) before being given the correct solution, or (c) read and copy the problem with its correct solution (i.e., errorless learning). Following this, learners were tasked to solve an analogous target problem that was similar but nonidentical to the source problem. Of interest, spontaneous transfer—applying the source solution to solve the target problem without a hint to do so—was more likely after learners had either been initially induced to fail or been exposed to failed solutions to the source problem, as opposed to only processing the correct source solution. Presumably, inducing source solution errors that are analogous to those typically encountered when solving a novel target problem may facilitate noticing or retrieval of the source problem, thus promoting successful spontaneous transfer when individuals learn from their past errors (Gick & McGarry, 1992).

Psychological mechanisms of inducing errors.

Because allowed and induced errors are both generated by learners, there may reasonably be some overlap between their underlying mechanisms. For example, like errors that are allowed to occur naturalistically, induced errors that are related to the cue may encourage elaborative processing during encoding that forms a richer memory trace (e.g., Huelser & Metcalfe, 2012). That is, generating cue-related errors may promote deeper levels of semantic processing (Craik & Lockhart, 1972) while activating associated concepts to create a more elaborate network that aids future recall.

Furthermore, induced errors may serve as mediators or secondary cues to retrieve the correct response (e.g., Cyr & Anderson, 2015; Huelser & Metcalfe, 2012; Kornell et al., 2009; Potts & Shanks, 2014). Some suggestive evidence for the nature of errors as mediators has been offered by Vaughn and Rawson (2012), who found that the learning benefits of induced errors may depend on the timing that corrective feedback is presented. Like Kornell et al. (2009), Vaughn and Rawson observed that incorrect guessing outperformed studying when feedback was administered immediately after participants had guessed

the targets of weak associates. However, when feedback was given only after a delay, incorrect guessing led to poorer recall than studying. Presumably, delaying corrective feedback may increase the difficulty of covertly retrieving one's earlier guess, thereby hampering the encoding of one's incorrect guess as a mediator of the cue–target pair. Consistent with this view, Cyr and Anderson (2015) noted that participants in their study remembered their conceptual guesses better than their lexical guesses and that better memory for one's prior guesses predicted successful recall of the correct target, suggesting that errors may function as “stepping stones” toward the target.

When allowed and induced errors are paired with error management instructions that frame errors positively, active exploration (e.g., during trial-and-error) and encouragement of errors may both contribute to the effectiveness of these approaches. Indeed, Keith and Frese (2005) found that EMT enhances both cognitive and emotional self-regulation, such that metacognitive activity (e.g., generating hypotheses, observing changes, deriving general rules, and explicit explanations) and emotion control (i.e., strategies for regulating negative emotions) during training independently mediate the positive effects of EMT on adaptive transfer performance. In an attempt to dissociate the elements of active exploration and error encouragement, a meta-analysis by Keith and Frese (2008) compared EMT with proceduralized training (no exploration and no error encouragement) and exploratory training (exploration but no error encouragement). Notably, comparisons of EMT with proceduralized training yielded higher effect sizes than comparisons of EMT with exploratory training, suggesting that exploration exerts a significant influence on training outcomes. Simultaneously, comparing EMT with exploratory training yielded a small but significant mean effect size, indicating that error encouragement is effective in EMT.

However, few (if any) studies have distinguished between the mechanisms underlying errors that are allowed versus induced, even though there may be important differences between them. One key distinction, for example, relates to learners' confidence about their responses. When errors are allowed, learners may sometimes generate incorrect responses that they falsely believe to be correct (i.e., high-confidence errors). However, induced errors are often low-confidence errors—learners are, more often than not, clearly aware that their responses are incorrect (e.g., Kang et al., 2011). Accordingly, the learning benefits of induced errors may be less parsimoniously explained by increased attention to corrective feedback stemming from learners' surprise upon discovering that they are wrong (e.g., Fazio & Marsh, 2009). Directly comparing the effects of allowed and induced errors, and addressing the potential differences between their

underpinnings, thus present valuable endeavors for future research.

Educational implications of inducing errors. Given that inducing errors is not detrimental for learning and is, in fact, often helpful when immediate feedback is provided, educators may actively build challenge into their lessons through questioning to induce errors on the part of their students. In particular, the Socratic method of questioning involves teaching through asking a series of questions aimed at stimulating dialogue and critical thinking, rather than through direct instruction (Paul & Elder, 2006, 2007). As part of the Socratic method, teachers pose exploratory questions to probe their students' thinking and uncover gaps in their knowledge about the subject matter (e.g., Paul & Elder, 2006; Tofade, Elsner, & Haines, 2013). Building on this method of questioning, teachers can regularly challenge their students with questions to induce erroneous responses that can, then, be used as key points for class discussion while enhancing learning.

The level at which teachers pose such questions to induce errors on the part of their students may also be important in shaping the learning that occurs. Indeed, educational psychology research has demonstrated that student achievement benefits from teacher questioning behavior that includes asking high cognitive level, divergent questions that afford for a variety of responses while demanding the synthesis of information, rather than mere verbatim recall or recognition (e.g., Redfield & Rousseau, 1981; Tofade et al., 2013; Wilen & Clegg, 1986). As Jensen, McDaniel, Woodard, and Kummer (2014) demonstrated, students who are consistently tested with high-level questions (e.g., questions involving application, evaluation, and analysis) rather than low-level questions (e.g., memory-oriented questions) acquire deeper conceptual understanding and better memory for the material. Accordingly, by routinely inducing errors through high-level questions and discussing their students' erroneous responses within a psychologically safe environment that welcomes and values the expression of diverse thoughts and opinions (e.g., Tofade et al., 2013), teachers may stimulate their students' critical thinking and mastery of the subject material.

To create desirable difficulties that enhance learning, however, such high-level questions must be optimally challenging—overly demanding questions may induce undesirable difficulties and impede learning instead (e.g., E. L. Bjork & Bjork, 2014). For instance, in a comparison of rereading a text (i.e., errorless learning) on posterior probability versus elaborative interrogation while reading the text in which learners answered complex “how” and “why” questions that led to many erroneous responses, Clinton, Alibali, and Nathan (2016) found that, contrary to their expectations, elaborative interrogation produced

poorer learning than rereading. Presumably, elaborative interrogation may have been too difficult and overwhelming for learners with low domain knowledge when combined with understanding the relatively complex logical reasoning behind posterior probability (Clinton et al., 2016; for a review, see Dunlosky, Rawson, Marsh, Nathan, & Willingham, 2013). In the absence of feedback, learners' incorrect responses may also have hampered their ability to make meaningful connections among ideas in the text, thereby hindering their acquisition of knowledge (see also Berthold & Renkl, 2009). Hence, in line with the “Goldilocks principle”—one of 25 principles of learning from the Association for Psychological Science—that learning material should not be too easy or too difficult, but “just right” for learners' level of skill and prior knowledge (Graesser, Halpern, & Hakel, 2008), it may be essential for teachers to pitch high-level questions at varying degrees of challenge corresponding to their assessment of their students' state of knowledge while providing appropriate feedback during class discussions.

As compared to allowing “naturalistic” errors to occur, inducing errors may enable teachers to better anticipate the mistakes that their students may make and to prepare appropriate feedback more effectively. However, for both allowed and induced errors, increased frustration and reduced self-efficacy may arise if learners attribute their errors to internal, stable, and uncontrollable causes such as low ability (Lorenzet et al., 2005; Weiner, 1985). To ameliorate these negative consequences, guiding learners into making specific errors may be considered instead.

Guiding Errors

As a second type of error promotion, errors are explicitly incorporated into the learning process by intentionally instructing or actively guiding learners into specific errors in a structured manner during training (Lorenzet et al., 2005). Accordingly, such errors are often systematically preselected by teachers so that learners experience a common set of errors, rather than being exposed to more spontaneous or naturally occurring errors during active exploration. For instance, in Lorenzet et al.'s (2005) guided error training approach, a subject matter expert first identified common errors that occur when learning and using Microsoft PowerPoint. Trainees were then given click-by-click instructions and led to make these errors before being shown how to correct them. As compared to error-free trainees who received similar click-by-click instructions but were led through the training without errors, guided-error trainees subsequently displayed significantly faster and more accurate performance across both reproduction tasks (i.e., tasks involving the reproduction of

skills learned during training) and generalization tasks (i.e., tasks involving skills not directly covered during training).

Research on guiding errors remains curiously sparse in applied psychology and workplace training literature, however. Although training research has examined how learners can be exposed to specific errors, these are often presented as other-generated errors when observing errors (e.g., Ivancic & Hesketh, 2000; Joung et al., 2006), as opposed to having learners commit these errors themselves. At the same time, empirical studies on guided errors are almost nonexistent in the fields of cognitive and educational psychology—whereas several researchers have investigated how errors can be promoted by inducing them during forced guessing (e.g., Kang et al., 2011; Kornell et al., 2009; Potts & Shanks, 2014), deliberately leading learners into making a priori identified errors remains relatively novel ground.

Psychological mechanisms of guiding errors.

Why did guided error training produce better posttraining performance than error-free training in Lorenzet et al.'s (2005) study? Given that guided-error and error-free trainees reported similar levels of self-efficacy immediately after training, it does not seem to be the case that guided errors enhanced learning through increased self-efficacy beliefs (e.g., Zimmerman, 2000). Rather, error commission and error correction may, independently or together, account for the benefits of guided error training. For instance, being guided into errors may enable learners to recognize incorrect responses and strategies that they should avoid in the future. Moreover, when learners are guided out of these errors, they receive richer feedback that may direct their attention to task processes that improve performance (e.g., Kluger & DeNisi, 1996; Lorenzet et al., 2005). To pin down the precise mechanism(s) underlying guided errors, it is vital that future studies disentangle the contributions of error commission and supported error correction.

Educational implications of guiding errors. In contrast to the idiom “no pain, no gain,” guided errors promote learning while minimizing negative emotional responses through allowing learners to veridically attribute their errors to the training approach and presenting statements that frame errors as positive learning events (e.g., Reason, 1990). Applied in educational contexts, teachers can implement similar techniques to guide their students into and out of errors. For example, when imparting research design concepts and skills, teachers may inform their students that errors will be included as an intended part of the learning experience, before guiding their students into designing experiments that are riddled with confounds and are meant to fail. Class discussions can then be initiated to explain why such experiments are

poorly designed, and teachers can guide their students to discover how these experimental designs can be improved.

Concurrently, educators may explore error correction methods that promote students' self-regulated learning. Although Lorenzet et al. (2005) employed supported error correction in which trainees were guided out of errors, learners are typically expected to work through and correct errors on their own in most other error training procedures (e.g., Dormann & Frese, 1994; Frese et al., 1991; Keith & Frese, 2005). As earlier discussed, however, discovery is enhanced when teachers scaffold or provide additional guidance during the exploration process (e.g., Alfieri et al., 2011). Hence, instead of having learners independently correct the errors they are guided into or providing them with the solutions entirely, teachers may use an assisted error correction approach in which students are asked to self-assess their performance and correct their errors based on handouts containing details about what correct responses entail (e.g., Zamora, Suárez, & Ardura, 2018). Peer collaborations can also be incorporated by having students work in pairs or small groups to review, discuss, and correct the errors they have commonly made. In this way, learners are provided with both informational feedback and more opportunities to develop appropriate metacognitive skills during error correction.

As these suggestions indicate, guiding learners into and, subsequently, out of errors is amenable to implementation in a variety of classroom settings. In contrast to allowing and inducing errors, it also allows for errors to be used more systematically in learning, whereby teachers can pre-identify common errors to introduce in their classes and prepare relevant feedback on these errors for their students. Furthermore, because students are guided into making and experiencing the same errors as their peers, this may level the playing ground in the classroom and promote a culture of error embracement by developing healthy attitudes toward learning from one's errors and encouraging peer cooperation to resolve errors.

GENERAL DISCUSSION

As this review has highlighted through a 3P framework of approaches to errors, the various techniques of avoiding, observing, allowing, inducing, and guiding errors can each potentially benefit learning when appropriately applied in specific contexts. In high-stakes contexts, for instance, errors can be costly and should reasonably be avoided—the Darwin Awards that are bestowed posthumously on ill-fated individuals who eliminate themselves from the gene pool through their own foolish mistakes are, perhaps, a clear testament to this. Yet, in some low-stakes learning contexts, making errors may create

opportunities for potential educational benefits to be reaped. As Schoemaker (2011) suggested, errors can be classified as *tragic* (high cost, low benefit), *serious* (high cost, high benefit), *trivial* (low cost, low benefit), or *brilliant* (low cost, high benefit). That is, not all errors are created equal: Whereas tragic mistakes such as getting into a car accident should be wholly avoided, brilliant mistakes such as making a groundbreaking scientific discovery through a lab error can be profitable (Schoemaker, 2011). Hence, the key question here is not whether learning with or without errors is more effective, but rather when and how to use errors to optimize learning.

Interactions With Learner Characteristics and Learning Contexts

The efficacy of each error approach in various learning contexts may depend on learners' characteristics. For instance, preventing errors through avoiding them may be helpful for individuals with memory and cognitive impairments (for a review, see Clare & Jones, 2008; cf. Middleton & Schwartz, 2012). Because prior errors may create more interference for individuals who are more reliant on implicit memory (Baddeley & Wilson, 1994), such learners may benefit more from avoiding errors during learning. In contrast, the advantage of avoiding errors may be reduced in individuals with intact or relatively superior explicit memory (N. D. Anderson & Craik, 2006). At the same time, allowing rather than avoiding errors appears to be more effective for the task performance and self-efficacy of individuals with high cognitive ability or who are more open to experiences, as compared to their counterparts with lower cognitive ability or who are less open to experiences (e.g., Gully et al., 2002; Loh, Andrews, Hesketh, & Griffin, 2013). Similarly, in line with the finding that novice and expert learners mentally represent and approach problems differently (Chi, Feltovich, & Glaser, 1981), learners with better prior knowledge profit more from observing incorrect and correct solutions than correct solutions only, whereas studying only correct solutions in worked examples (i.e., avoiding errors) is more favorable for learners with poor prior knowledge (e.g., Große & Renkl, 2007; Kalyuga et al., 2001; Tuovinen & Sweller, 1999). This suggests that applying the various error approaches according to learners' characteristics is important for increasing the efficacy of errors.

In situational contexts where learners fall prey to illusions of competence owing to misplaced feelings of "knowing" and a subjective sense of fluency when information is easily acquired (e.g., B. L. Schwartz, 1994), some error approaches may also be more beneficial than others. For example, learners' accurate assessments of their own knowledge may be further impeded when errors

are removed entirely (avoiding errors), or when room is provided for learners to externally attribute errors to others (observing errors) or the training paradigm (guiding errors). Instead, allowing and inducing errors may more effectively combat overconfidence through enabling learners to discover and experience the boundaries of their current knowledge (e.g., Ivancic & Hesketh, 2000). It must be noted, however, that the potential of allowed and induced errors to enhance learning may be shaped by learners' attributions—whereas attributing errors to internal and uncontrollable factors such as a lack of talent may impair subsequent performance by undermining self-motivation and intrinsic task interest, ascribing errors to temporary and controllable factors such as the use of ineffective strategies may sustain learners' motivation and task interest (e.g., Weiner, 1985; Zimmerman & Kitsantas, 1997, 1999). Hence, when allowing and inducing errors, it may be vital for educators to guide students' metacognitive processes and self-regulation by emphasizing adaptive interpretations of errors through self-reflective activities (for a discussion, see Zimmerman & Moylan, 2009).

Furthermore, the utility of each error approach may vary across different desired learning outcomes. For example, one important distinction pertains to whether the outcome of interest requires transfer to contexts within or outside of training. Notably, as compared to avoiding errors, observing others' errors has been found to produce poorer behavioral reproduction in contexts similar to those encountered during training but better behavioral generalization to novel contexts (e.g., Baldwin, 1992; Joung et al., 2006). Likewise, on analogical transfer tasks involving the application of learned solutions to solve similar problems, allowing errors during discovery learning offers little benefit over avoiding errors (e.g., Keith et al., 2010; McDaniel & Schlager, 1990), although inducing source solution errors that are analogous to target solution errors can facilitate spontaneous transfer relative to errorless learning (Gick & McGarry, 1992). Conversely, on adaptive transfer tasks demanding the development of novel solutions that have not been taught during training, allowing or inducing errors has been found to be more effective than avoiding errors even in learners with relatively low cognitive ability and motivation (e.g., Dormann & Frese, 1994; Keith et al., 2010). Of interest, guiding errors has been shown to produce superior performance than avoiding errors on both skill reproduction and generalization tasks, combined (Lorenzet et al., 2005). However, a prospect remains to be tested: Guided errors may be relatively more beneficial for analogical than adaptive transfer—the rich systematic feedback that learners receive when they are guided into and out of errors may facilitate the abstraction of useful rules or schemas that can be applied to similar tasks, but

simultaneously reduce opportunities for developing meta-cognitive skills that may be important for adaptive transfer on novel tasks if learners do not actively engage with the feedback they receive at a deeper, more personal level (Ivancic & Hesketh, 2000). Thus, the success of implementing different error approaches may depend, in part, on the key learning objective at stake.

The Role of Feedback in Error Correction

To optimize learning from errors, it is crucial that learners receive corrective feedback after they have erred (e.g., R. C. Anderson, Kulhavy, & Andre, 1972; Pashler, Cepeda, Wixted, & Rohrer, 2005), as incorrect responses are unlikely to be spontaneously corrected without feedback (Butler, Karpicke, & Roediger, 2008). Indeed, feedback has been viewed as one of the most potent influences on learning (for reviews, see Black & William, 1998; Hattie & Timperley, 2007). Although an exhaustive review of the abundant work in this area is beyond the scope of this discussion, we highlight some important factors related to how the efficacy of feedback can be enhanced to improve learning after errors have occurred (see also Metcalfe, 2017; Mulliner & Tucker, 2017).

First, *when* should feedback be provided? Timely feedback after assessments is generally considered to be good practice that is helpful for students' learning (e.g., Nicol & Macfarlane-Dick, 2006), particularly when the feedback is in time for students to undertake the next task (e.g., Dawson et al., 2018). Although students recognize timeliness as a characteristic of quality feedback (e.g., Beaumont, O'Doherty, & Shannon, 2011; Poulos & Mahony, 2008; for a review, see Li & De Luca, 2014), they do not appear to distinguish between timely and extremely timely feedback. For instance, Bayerlein (2014) found that undergraduate students did not perceive significant improvements in timeliness when feedback was provided in less than 11.5 days, whereas postgraduate students perceived feedback delivered within 2.5 and 5 days to be similarly timely. This suggests that teachers' effort to provide extremely timely rather than timely feedback may not be entirely necessary. In fact, Butler, Karpicke, and Roediger (2007) demonstrated that delaying the presentation of feedback by up to 1 day later rather than delivering it immediately is more advantageous for learning from one's incorrect (and correct) responses on a multiple-choice test, as a delay may allow for the accessibility of learners' initial incorrect responses to fade and thus potentiate learning of the corrective feedback when it is presented. Although several other studies have instead found that immediate feedback is more effective than delayed feedback (for a meta-analysis, see Van der Kleij, Feskens, & Eggen, 2015), one crucial mechanism that may reconcile these findings is the extent to which

learners attend to the feedback when it is presented—if feedback is received after too long a delay, learners' attention to it may wane, and they may be less likely to process it meaningfully and act on it (e.g., Butler et al., 2007; Metcalfe, 2017). Investigating the optimal timing of feedback across various learning domains and tasks thus presents a fruitful avenue for future research.

How should feedback be provided? The format of feedback presentation appears to have relatively little impact on students' subsequent learning, so long as students' processing of the feedback is controlled. For instance, Butler et al. (2007) did not observe any differences in students' performance on a delayed recall test as a function of whether the correct answer had been directly shown after students had erred on an initial multiple-choice test, as opposed to having students continue to respond until they had selected the correct answer. Moreover, students' subsequent learning does not seem to be differentially affected by the source of feedback in being purportedly generated by a computer or instructor (Lipnevich & Smith, 2009), suggesting that automatic feedback tutoring systems that provide timely feedback can potentially be used to support learning (e.g., Bayerlein, 2014).

In contrast, *what* feedback is given after errors is critical for students' subsequent learning. In memory recall tasks, learners profit from receiving feedback that specifies the correct response rather than merely "correct" or "wrong" information (Pashler et al., 2005), as well as feedback that elaborates on the correct answer (for a review, see Jaehnig & Miller, 2007). Relatedly, descriptive feedback that provides students with detailed information on correct responses and suggestions for improvement has commonly been considered to be more effective for learning than evaluative feedback that simply informs students about how well they have performed (e.g., Lipnevich & Smith, 2009; Nicol & Macfarlane-Dick, 2006). This distinction between descriptive and evaluative feedback may be particularly pertinent for higher order learning tasks such as essay writing, which demand far more than binary correct/wrong responses as in those typically required in memory recall tasks. That is, students need to know not only whether they have responded (in)correctly but also how they can proceed to achieve their learning goals (Hattie & Timperley, 2007).

Crucially, students must engage with and productively use the feedback they receive to improve their learning. Yet, educators have raised concerns that students may not even read the feedback provided to them (e.g., MacDonald, 1991), much less use the feedback to guide their subsequent work (e.g., Crisp, 2007), even if students themselves may report otherwise (e.g., Mulliner & Tucker, 2017). Poor feedback quality aside, learners' successful uptake of feedback may be impeded by problems

such as difficulty in interpreting the feedback (e.g., Price, Handley, Millar, & O'Donovan, 2010), “emotional backwash” when reacting poorly to negative feedback (Pitt & Norton, 2017), and a lack of knowledge about effective strategies to use the feedback formatively (for reviews, see Evans, 2013; Jonsson, 2012). Consequently, such difficulties in engaging with feedback may generate frustration and dissatisfaction among students and teachers (e.g., Price et al., 2010).

To some extent, teachers may ameliorate these problems and increase the likelihood of students acting on feedback by providing concrete suggestions for improvement through descriptive feedback (e.g., van der Pol, van den Berg, Admiraal, & Simons, 2008), guiding students more closely through scaffolding on the use of feedback (e.g., Jonsson, 2012; Orsmond & Merry, 2011), and striking a balance between providing positive and critical feedback (e.g., Weaver, 2006), much like the use of positive statements in EMT to counteract learners' potential frustration from making many errors (e.g., Ivancic & Hesketh, 1995/1996). For feedback processes to be sustainable in the long run, it may also be vital for teachers to systematically develop students' self-monitoring and evaluation abilities toward enabling them to independently improve their work (Carless, Salter, Yang, & Lam, 2011), in line with the saying “Give a man a fish and you feed him for a day; teach a man to fish and you feed him for a lifetime.” This can be accomplished through dialogic interactions in which teachers and students engage in discussions about learning (e.g., Carless et al., 2011; Price et al., 2010) and through providing students with opportunities to practice self-regulated learning via self-assessment and reflection tasks (e.g., Nicol & Macfarlane-Dick, 2006).

Directions for Future Research

In extending current discussions that have often centered on the dichotomous absence versus presence of errors in learning, this review has underscored the value of conceptualizing various approaches to errors in more specific and nuanced ways, given the complexities of each approach's effects and implications. Moving forward, it is thus imperative to develop deeper insight on each error approach within educational contexts to optimize learning. Although much research in cognitive and educational psychology has focused on errors that are allowed and induced, observed and guided errors have received relatively little attention thus far in spite of their promising benefits particularly when compared to errorless learning. Moreover, there is a dearth of research that has directly compared and contrasted the mechanisms of the various approaches to errors, as well as their consequences across a range of educational outcomes. For example, although it has been established that allowing learners to make errors

firsthand is superior to observing others' errors in enhancing recall of factual information (Metcalf & Xu, 2018) and hazard handling performance in driving (Wang et al., 2010), less can be said about how guided errors fare compared to observed, allowed, or induced errors.

Besides comparing the various error approaches in finer detail, future work may consider potential moderators of these approaches. In particular, given that the efficacy of errors varies depending on learners' prior knowledge (e.g., Große & Renkl, 2007; Kalyuga et al., 2001; Tuovinen & Sweller, 1999), it appears valuable to investigate how an optimal balance can be achieved across different stages of learning when giving learners assistance to prevent errors versus withholding help to promote errors (e.g., Koedinger & Alevan, 2007). The impact of errors can also be examined across different age groups and domains of learning to identify any potential boundary conditions constraining the utility of errors during learning.

In addition, cognitive and educational psychology studies have often investigated the effects of making errors on memory recall (e.g., Cyr & Anderson, 2015; Kang et al., 2011; Kornell et al., 2009) but seldom in relation to higher order learning outcomes such as evaluation and application, with some exceptions (e.g., Klahr & Nigam, 2004). Consequently, the advantages of generating errors in more complex educational tasks (e.g., learning and applying a scientific principle, developing good research questions) beyond those in workplace training research remain tenuous. Hence, it is vital for future work to conduct more controlled studies that pit the various error approaches against one another across a wider variety of learning outcomes in order to thoroughly probe their relative effects. Thereafter, it may further be useful to test the efficacy of combining error approaches at different stages of learning and knowledge acquisition.

Furthermore, several studies in cognitive and educational psychology have not precisely dissociated the effects of making errors from those of active learning. That is, active errorful learning approaches have often been pitted against passive rather than active errorless learning conditions. For instance, in studies where the errorless learning control condition simply involves exposing learners to correct information (e.g., Grimaldi & Karpicke, 2012; Huelser & Metcalfe, 2012; Kornell et al., 2009), learners are not given any opportunities to respond incorrectly but also do not make any active or overt response at all, in contrast to errorful learning conditions that require learners to generate incorrect responses or guesses. This is problematic because even where erroneous responses are concerned, overtly making an error leads to better recall than covertly producing one (Metcalf & Xu, 2018), and generating errors produces better memory than simply choosing incorrect responses (Potts & Shanks, 2014). Moving forward, active errorless learning conditions

can potentially involve, at the very least, participants reading aloud (e.g., Slamecka & Fevreski, 1983) or writing/copying the correct targets (e.g., Baddeley & Wilson, 1994; Kornell, Klein, & Rawson, 2015). In sum, the use of more rigorous comparison conditions is critical to determine the relative impact of various error approaches and to isolate their mechanisms.

Another area for future research involves identifying learners' intentions and motivations when making various errors. This is especially pertinent, as errors can be generated through many pathways. In the field of human error, for instance, a key distinction has been made between *slips* and *mistakes*—whereas slips occur when learners execute incorrect actions that are not what were correctly intended, mistakes are errors resulting from incorrect intentions or knowledge that correspondingly lead to incorrect actions (Norman, 1981; Reason, 1990). For example, a slip occurs when a pianist plays an incorrect note by accidentally striking a wrong key. However, when the incorrect note is played because the pianist had misread the music score to begin with, a mistake has been produced. Reason (1990) further extended this framework of human error to include *lapses* (execution errors similar to slips, but in more covert forms that typically involve failures of memory) and *violations* (deliberate deviations from socially appropriate practices).

Such differences among error types underscore the importance of identifying learners' prior intentions when classifying their errors. Because learners may commit errors for various reasons, the same incorrect response may result from different intentions that are not immediately apparent given behavioral data alone (Frese & Altmann, 1989). Yet few empirical studies, particularly those outside of human error research, have explicitly made such nuanced differentiations among various classes of errors. As a result, the underlying mechanisms and learning consequences of each error type remain largely unclear. To address this gap, it is essential that future cognitive and educational psychology research categorizes "errors" at a more specific level of detail toward making finer distinctions among them.

CONCLUSION

Whereas students and teachers often strive to avoid errors, mistakes are essential to growth and the learning process. The present review has put forth a 3P framework of approaches to error occurrence during learning that includes error prevention (avoiding or observing errors), permission (allowing errors), and promotion (inducing or guiding errors). Depending on the characteristics of learners and the specific learning context at hand, each error approach may offer unique benefits for learning when used appropriately to accomplish a corresponding

educational objective. To harvest meaningful gains from the various error approaches, it is thus crucial for future work to investigate how errors can be systematically and effectively integrated in education to enhance learning, toward developing a culture of honoring our mistakes and realizing the potential to actively learn from them. Indeed, to err is human, but to learn from our errors is divine.

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