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The impact of error frequency on errorless and errorful learning of object locations using a novel paradigm

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ABSTRACT
Errorless learning (EL) is an approach in which errors are eliminated or reduced as much as possible while learning of new information or skills. In contrast, during trial-and-error – or errorful – learning (TEL) errors are not reduced and are often even promoted. There is a complex and conflicting pattern of evidence whether EL or TEL may result in better memory performance. One major confound in the extant literature is that most EL studies have not controlled for the number of errors made during TEL, resulting in a large variability in the amount of errors committed. This variability likely explains why studies on the cognitive underpinnings of EL and TEL have produced mixed findings. In this study, a novel object-location learning task was employed to examine EL and TEL in 30 healthy young adults. The number of errors was systematically manipulated, allowing us to investigate the impact of frequency of errors on learning outcome. The results showed that recall from memory was significantly better during EL. However, the number of errors made during TEL did not influence the performance in young adults. Altogether, our novel paradigm is promising for measuring EL and TEL, allowing for more accurate analyses to understand the impact of error frequency on a person's learning ability and style.

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Errorless learning; trial and error learning; spatial memory; error monitoring

Functioning in daily life requires us to constantly monitor and learn about the consequences of occurring events, thus allowing us to learn what to expect and how to behave in a particular environment (Firston, 2010). Negative outcomes, such as errors, are particularly salient and effective learning cues (Holroyd & Coles, 2002). Recent theories of learning postulate that we use such negative outcomes to update our expectations of the world and adapt (referred to as trial-and-error [TEL] or errorful learning) (e.g., Mathys et al., 2014; Mathys, Daunizeau, Friston, & Stephan, 2011).

Several studies have demonstrated that TEL can be beneficial, depending on factors like the timing of feedback (Kang et al., 2011; Kornell, 2014), the presence of a relationship between a recall cue and the target stimulus (Bridger & Mecklinger, 2014; Grimaldi & Karpicke, 2012; Huesler & Metcalfe, 2012; Middleton & Schwartz, 2012), the level at which a cue is processed, and whether retrieval is semantic or episodic (Knight, Ball, Brewer, DeWit, & Marsh, 2012). The importance of TEL is also accentuated in Bjork's notion of Desirable Difficulties (Bjork, 1994; Schmidt & Bjork, 1992), which postulates that learning should be made as challenging as possible for a better long-term retention and transfer. This can be achieved by, for instance, varying the conditions of practice, providing contextual interference, reducing feedback, or using tests as learning events (see, e.g., Bjork & Kroll, 2015; Bufe & Aslan, 2018; Kachergis, Rhodes, & Gureckis, 2017). The beneficial effects of error-based have also been demonstrated in patients with executive dysfunction. For instance, a randomised controlled trial found that patients with severe traumatic brain injury benefited more from TEL than EL to strengthen generalisation of skills, self-awareness and behavioural competency (Ownsworth et al., 2017).

Although TEL is often effective, learning sometimes may be more successful without the occurrence of errors, resulting in superior performance to TEL, especially in individuals with cognitive impairment (Baddeley & Wilson, 1994;

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Bertens & Brazil, 2018; Clare & Jones, 2008; Kessels & De Haan, 2003). This form of learning has been termed errorless learning (EL) (Ferster & Skinner, 1957; Terrace, 1963). During EL, consolidation of information occurs after a single observation of an event that leads to a positive outcome, resulting in more accurate recall of information relative to TEL (Terrace, 1963). EL, compared to TEL, seems to be a more beneficial strategy to improve task performance in patients with an amnesic syndrome (Callahan & Anderson, 2019; Roberts et al., 2018; Wilson, Baddeley, Evans, & Shiel, 1994), mild to moderate dementia (de Werd, Boelen, Olde Rikkert, & Kessels, 2013; Kessels, Feijen, & Postma, 2005; Kessels & Olde Hensken, 2009), severe dementia (Ruis & Kessels, 2005), traumatic brain injury (Bertens, Kessels, Boelen, & Fasotti, 2016; Bertens, Kessels, Fiorenzato, Boelen, & Fasotti, 2015; Clare & Jones, 2008; Evans et al., 2000), alcoholic Korsakoff's syndrome (Komatsu, Mimura, Kato, Wakamatsu, & Kashima, 2000; Rensen, Egger, Westhoff, Walvoort, & Kessels, 2017, 2019), aphasia (Middleton, Schwartz, Rawson, & Garvey, 2015). Also, beneficial effects of TEL have been found in healthy older adults (Guild & Anderson, 2012; Lubinsky, Rich, & Anderson, 2009). Note that the few studies exploring the effects of EL in healthy individuals have indicated that EL may also have a positive effect on memory performance in healthy young adults (Hammer, Mohammadi, Schmicker, Saliger, & Münte, 2011; Heldmann, Markgraf, Rodríguez-Fornells, & Münte, 2008; Kessels, Te Boekhorst, & Postma, 2005), although the findings in young adults are mixed (see, e.g., Kessels & De Haan, 2003). Taken together, the complex and conflicting pattern of findings has made it challenging to assign superiority to either EL or TEL.

The lack of knowledge about the mechanisms through which EL occurs also acts as a further complicating factor. For instance, Baddeley and Wilson (1994) suggested that the beneficial effects of EL they observed in amnesic individuals during a word completion task reflected a faulty explicit memory system, whereas implicit memory remains intact. Hunkin, Squires, Parkin, and Tidy (1998), in contrast, argued that EL is supported by what they refer to as "residual explicit memory", even in amnesic individuals with impaired explicit memory (for an overview see Bertens & Brazil, 2018). The most recent theory proposes that the mechanism underlying the effects of EL relies on executive function (Clare & Jones, 2008). According to this view, executive control processes play an important role in information processing, supporting working memory and encoding of information into episodic memory. These executive processes are able to compare external stimuli with stored internal representations and integrate this knowledge, for instance about source or context, with the content of an event. Hence, executive dysfunction is associated with the inability to detect and monitor errors, and to modify behaviour based on observed outcomes. As a consequence of poor error-monitoring, errors might not be recognised as an incorrect response and will be erroneously stored in memory. These stored errors might interfere with the correct response during retrieval.

What the theories of Baddeley and Wilson (1994), Hunkin et al. (1998) and Clare and Jones (2008) have in common, is that the beneficial effect of EL would stem from a reduced competition between correct and erroneous responses, indicating that a cognitive control system is crucial for monitoring the outcomes (Bertens & Brazil, 2018; Burgess, 1996; Schnider & Ptak, 1999). Brain research on error and conflict processing has shown that the error-related negativity (ERN), a negative electrophysiological deflection that can be observed within 100 ms after an error is detected, reflects the engagement of an error-monitoring system (Bertens & Brazil, 2018; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993). Rodríquez-Fornells, Kofidis, and Münte (2004) hypothesised that, during the EL and TEL condition of a word-stem completion task, the modulation of the ERN amplitude should reflect the activity of the error-monitoring system that verifies the accuracy of retrieval memory traces. They found response ERN-like activity during memory retrieval, possibly reflecting the engagement of the error-monitoring system. However, the ERN amplitudes were similar for EL and TEL condition. Other studies have also failed to find clear differences in ERN amplitudes between EL and TEL (Hammer, Kordon, Heldmann, Zurowski, & Münte, 2009; Heldmann et al., 2008).

Furthermore, an fMRI study of Hester, Barre, Murphy, Slik, and Mattingley (2008) showed that error-related posterior medial frontal cortex (pMFC) activity was related to immediate adaptive changes in response behaviour, that is, participants changed their behaviour immediately after they made an error. Participants had to learn the spatial location of 2-digit numbers from an 8×8 matrix. During the recall phase, one of the locations would be highlighted and the participant had to respond with the number associated with that location. The recall response was immediately followed by feedback about the accuracy and the correct response, allowing participants to learn from their errors. The recall phase consisted of 3 rounds of 8 recall trials within a block, so that each location was highlighted three times in total. They found a higher level of error-related neural activity in the pMFC for initial errors that were subsequently corrected than for repeated errors. Also, activity in the pMFC and hippocampus during recall errors were related to future responses. They argued that error-related pMFC activity is affected by outcome expectancy, with higher levels of activity when the actual outcome was worse than the predicted outcome (see, e.g., Holroyd & Coles, 2002).

Bertens and Brazil (2018) have identified various issues that may have contributed to the lack of clear results. One such issue concerns the design of the current EL tasks regarding the superiority of EL or TEL. For instance, in the commonly used word-completion task (Baddeley & Wilson, 1994) participants were given the first two letters of a five-letter word by the experimenter and were asked to guess the word the experimenter had in mind. In the EL condition, the correct answer was given instantly by the experimenter. During the acquisition phase of the TEL condition, it was possible to guess the correct answer in either a second try, third try, fourth try or maybe not at all. Because of this, the occurrence of errors was not controlled and may have resulted in an uncontrolled variation of error frequency in TEL conditions across participants. This lack of control over the occurrence of errors could be a large source of variability in these learning studies. Clare and Jones (2008) also pointed out that different studies did not report the occurrence of unintended errors during the acquisition phase of EL. In a recent study, Cyr and Anderson (2018a) manipulated whether or not errors were made during learning of cue-target pairs. Participants were shown a homographic cue (e.g., *port*) associated with a primary meaning (e.g., *boat* and *dock*) and a secondary meaning (e.g., *wine* and *brandy*). Participants were then instructed to guess the corresponding target (e.g., "*is it* sailor?"). The correct target was either semantically related to the guess in the "match trials" (e.g., *boat*) or unrelated in the "mismatch trials" (e.g., *wine*). In the TEL condition, the correct target word was always another word than the generated guess, because the experimenter always had two alternatives as possible targets for each the primary meaning (e.g., *boat* and *dock*) and secondary meaning (e.g., *wine* and *brandy*), and selected the target that was not given by the participant. The experimenter pointed out that the correct target was "boat" in the semantically related match trials, or "wine" in the semantic unrelated mismatch trials. By doing so, participant always made one error during TEL, while during EL, the cue (e.g., *port*) was immediately followed by the target (e.g., *boat*). The authors found a beneficial effect of making errors during learning compared to EL when the number of errors is controlled for.

In the present study, we employed a novel spatial learning task (i.e., the "Drawer Task") in a group of healthy young adults to examine learning and recall during EL and TEL, in which the frequency with which errors occurred (i.e., 0, 2, 3, 4 or 5 errors) during learning was pre-determined. Note that in the paradigm used by Cyr and Anderson (2018a) participants always made just one error. By controlling the number of errors, we sought to obtain a more accurate view on the effect of error frequency on the learning process. Also, the visuospatial nature of the task may add to the ecological validity. Previously used tasks involved memorising word pairs or completing five-letter words, which are cognitive tasks that are not often required in everyday life. In contrast, our task mimics scenarios that occur often by asking participants to place common objects in a drawer and to remember the location of these objects. Based on this notion, Kessels, Feijen, et al. (2005) employed a task in which participants had to learn the locations of everyday objects in one of five rooms (living room, bedroom, study room, bathroom and kitchen). Participants were instructed to place the object at its correct location, which was indicated by a white square in the EL condition. In the TEL condition, participants were given the same instruction, but had to choose between three possible locations indicated by white squares. The target location of the objects was always the location which was not the least and not the most frequent choice of the three possible locations. It was found that young adults were better in relocating everyday objects after EL than TEL on a spatial memory task. Based on these findings, combined with the aforementioned results suggesting better EL performance in various populations, we hypothesised that general performance during recall should be superior after EL compared to TEL during our spatial memory task as well. Our second goal was to investigate whether the frequency of errors had an impact on recall performance. Based on the EL theories, it could be hypothesised that recall performance would be worse when a higher amount of errors was committed during learning. This is because having more memory traces have been related to an increased engagement of the error-monitoring system, adding extra cognitive load and ultimately resulting in worse performance (see Baddeley & Wilson, 1994; Clare & Jones, 2008; Hunkin et al., 1998). However, the findings by Rodríquez-Fornells et al. (2004), Hammer et al. (2009) and Heldmann et al. (2008) suggested that error frequency has no influence on the strength of the engagement of the error-monitoring system. Thus, these conflicting views make it difficult to generate a clear prediction for the directionality of the effect of error frequency in our task and emphasise the importance of systematically exploring the impact of error frequency on learning.

Methods

Participants

Power calculations for the comparison of error rate, assuming a medium effect size ($r = 0.30$) and a power of $(1\text{-}\beta) = 0.85$, showed that a minimum sample size of 15 was required. In this study, 30 undergraduate students between the age of 18 and 26 years ($M = 21.1$, $SD = 2.24$; 13 males) were recruited from Radboud University and HAN University of Applied Sciences in Nijmegen, the Netherlands. All participants were high functioning individuals and none reported subjective cognitive complaints. Intelligence was estimated with the Raven's Advanced Progressive Matrices – Short Form (Raven, 1976) (IQ; $M = 116.7$, $SD = 12.6$). Participation was voluntary, participants gave written informed consent and received no compensation. The study was approved by the ethics review committee of the Faculty of Social Sciences of Radboud University (ECG2012-13 04-025).

Task

The Drawer Task is a computerised learning paradigm that measures memory for object locations after EL and TEL. The task consisted of an acquisition phase, followed by an intentional recall phase. At the beginning of each trial during acquisition, participants were presented with a drawer unit consisting of 25 drawers (in a 5 × 5 layout) and were instructed that the main goal was to find out in which drawer each of 20 different objects (e.g., a teddy bear, a baseball cap) were stored and to memorise the location of each object. Each object appeared at the bottom of the screen, underneath the drawer unit (see Figure 1), and the correct location (i.e., the drawer in which the object was "hidden") had to be found by clicking on the drawers. If the correct drawer was selected, a blue square was presented around that drawer after which a lock appeared on the correctly selected drawer, indicating that that drawer was made unavailable for the remainder of the learning phase (as a drawer could only contain one target object). If an incorrect drawer was selected, a red square was shown around that drawer and participants had to click on another drawer until the correct one was found.

All participants performed one complete EL condition consisting of 20 trials in which no errors could be made. That is, every first allocation of an object into an available drawer was considered to be correct. Participants were instructed to place the objects randomly in the drawers and remember the location of these objects for later recall.

In the TEL condition, the number of different drawers that had to be selected before the "correct" location was found was pre-set. That is, the correct storage location for some objects was "found" at the first attempt (i.e., an errorless item), while others required 2, 3, 4, or 5 incorrect unique drawers to be chosen before the correct one was found (i.e., trial-and-error items), containing both errorless and trial-and-error items. This manipulation resulted in "correct" object locations that differed across individuals, as the number of unique selected "incorrect" drawers determined whether an object was "found" and not its location. Other objects were used during TEL than EL. All objects and trial types were presented in the same order for each participant, with 4 trials per error frequency manipulation (i.e., 4 items that were found after 1 correct attempt, 4 after 2 incorrect attempts, 4 after 3 incorrect attempts, etc.). Also, the error frequency manipulation occurred in randomised order in the TEL condition to make sure the number of incorrect attempts required could not be anticipated.

The recall phase followed immediately after the acquisition phase of each condition. Here, the same drawer unit was presented to the participants, and the objects were shown serially underneath the chest of drawers. Participants were instructed to place each object into the correct drawer (that is, the drawer in which the object was stored in the acquisition phase), thus requiring them to recall the location of each object from memory. The objects were presented in a randomised order, and no feedback about the accuracy of their choices was provided. The drawers were not "locked" after each allocation and self-corrections were not allowed. The EL block was always presented before the TEL block to the participants to prevent that the interference of the pre-set errors during the acquisition phase of TEL would transfer to the EL condition, thus contaminating the EL performance. The entire task was performed without any time constraints and lasted approximately 25 min.

The performance of the participants was measured in three ways. The first measure was the *mean of the sum of errors* made during the free recall across participants (i.e., the "error score", for which each incorrectly placed object during the recall phase counted as one error). In other words, during the recall phase the participant got one attempt to place an object in the correct drawer as was determined in the learning phase. When the participant placed the object in an incorrect drawer, irrespective of which drawer, this was counted as an error. The total amount of errors possible, i.e., the total error score, was 20, as the recall phase consisted of 20 trials. The second measure was a *"city block" displacement index*, in which for each object the distance between the correct drawer for an object (as determined in the learning phase) and the drawer chosen for that object during recall was computed as the sum of the number of drawers in the horizontal and vertical direction between the correct drawer and the drawer chosen. For instance, when a participant put the object two drawers below and two drawers to the right of the correct drawer during the recall phase, the city-block displacement index would be four in this trial, since there were four drawers between the chosen drawer and the correct drawer. A total city-block score was calculated by summing the city-block distances across all trials for each participant, from now on referred to as the "displacement score" (following the terminology introduced by Bucks & Willison, 1997; see Figure 1), with a maximum score of 160 given that the largest possible distance per trial is 8. The third measure was the *mean diagonal distance* in arbitrary units, defined as the absolute length of the diagonal between the maximum horizontal and vertical city-block distance for each item, averaged across all 20 items (i.e., the "distance score"; see Figure 1). For example, if an object is placed in an incorrect drawer located two drawers below (i.e., the vertical distance is 2) and two drawers to the right (i.e., the horizontal distance is 2) of the correct drawer, the length of the diagonal would be 2.83 in arbitrary units according to Pythagorean Theorem.

Data analysis

To address our research question whether EL performance was superior to TEL performance in our task, a repeated-measures General Linear Model (rm-GLM) analysis was

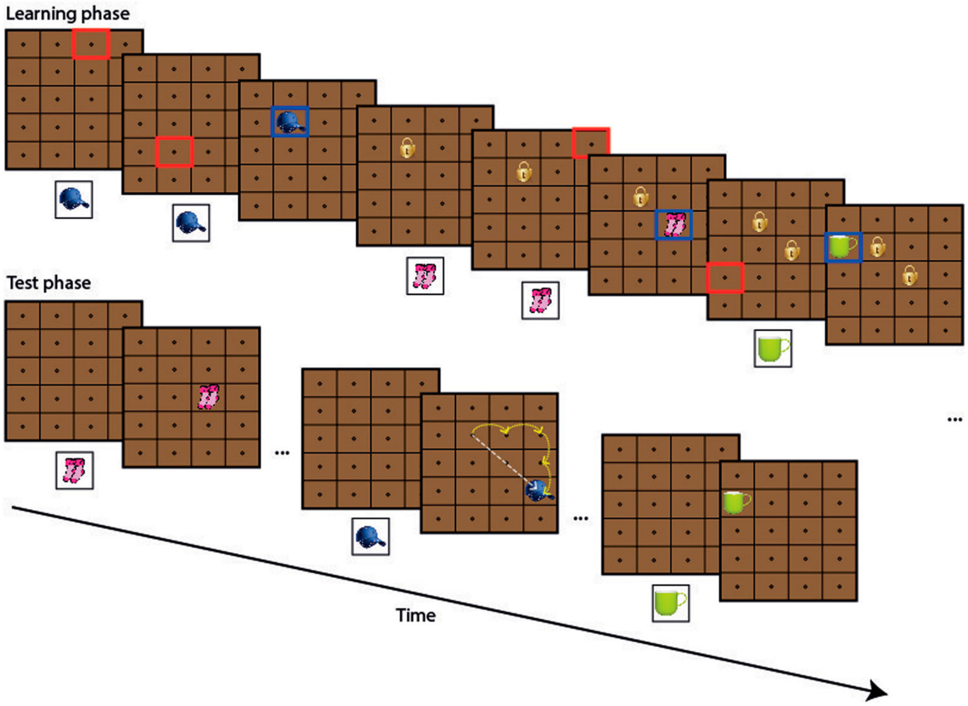

Figure 1. Schematic overview of the Drawer Task. In the learning phase, participants have to find the correct drawer in which a target object (shown at the bottom of the screen) is hidden. If an incorrect drawer is selected, a red square appears and the participant has to select another drawer, until the correct drawer is found. Then, a blue square appears indicating the participant has to memorise the object location and that drawer is subsequently "locked". Thereafter, the next object is shown, which has to be found. The top panel shows the learning phase for a two-error (three attempts) trial (the baseball cap), followed by two one-error (two attempts) trials (the socks and the cup). In the recall phase, the objects appear in random order and the participant must place them in the correct drawer. The white arrow indicates the distance score (i.e., the absolute distance between the original location and the repositioned item), the yellow arrows indicate the city-block displacement score (i.e., the number of drawers the item is removed from the original drawer, in this example 4).

conducted first with the learning condition (EL block, TEL block) as a within-subject factor and the error score, displacement score and distance score as possible dependent variables. As participants in the EL condition made fewer errors in total during the recall phase, resulting in a lower sum for the city-block scores across all trials in the recall phase, we additionally calculated the mean of the displacement score per error made in the recall phase by taking only the city-block scores into account when a participant made an error, instead of summing the city-block distance across all trials. By taking only the trials in which an error occurred into account, we examined whether the performance differed during EL and TEL when participants made an error and a second rm-GLM was executed with the mean of the displacement score per error frequency as dependent variable. Supplementary, to examine whether the performance on the errorless items of both EL and TEL differed during a mere EL condition or when errorless items were mixed with trial and error items, the Marascuilo procedure (Marascuilo, 1966; Michael, 2007) was employed to test whether the proportion of incorrect recalls according to error scores, displacement scores and distance scores, respectively, differed during the EL block (20 trials) and for the errorless items of the TEL block (4 trials). The Marascuilo procedure is a non-parametric approach for determining equality of proportions through simultaneous testing of the different possible pairs of proportions when there are unequal trial counts between conditions. For instance, participants made a total of 149 incorrect recalls during the EL block and the total amount of trials performed in the EL block was 600 (20 trials × 30 participants), so the proportion of errors was 149/600 (p_{EL}), while the proportion of errors for the zero-error trials included in the TEL block was 60/120 (p_{TEL}). The difference of proportion of errors during the EL block and TEL block was computed (e.g., error score: p_{EL}-p_{TEL} = .252) and the absolute difference of proportion of errors would be the test-statistic. Then the significance level ($\alpha = 0.05$) and the degrees of freedom ($k = 2$) were selected and the corresponding critical values to the absolute difference in the proportion of errors were calculated from

$$r_{EL,TEL} = \sqrt{(\chi^2_{1-\alpha}, k-1)} \\ {}^{*}\sqrt{(pEL(1-pEL)/nEL) + (pTEL(1-pTEL)/nTEL)}.$$

When the test statistic exceeded the critical value (e.g., $r_{EL,TEL}$ = .096), the pair of proportion was significant.

To examine the role of error frequency, a third rm-GLM was performed for the TEL condition only with the error frequency (performance on the 0, 2, 3, 4 and 5-error trials) as within-subject factor and the error score, displacement score and distance score, respectively, as dependent variables to explore if the performance is influenced by the

Figure 2. The mean error score, displacement score and distance score and standard error of the mean for the errorless and the trial-and-error condition.

number of erroneous attempts committed during the acquisition phase.

Results

For each of the three measures, performance was significantly better in the EL condition relative to the TEL condition (error score: $F\ (1,29) = 97.0$, $p < .001$, $\eta_p^2 = .770$; displacement score: $F\ (1,29) = 48.4$, $p < .001$, $\eta_p^2 = .625$; distance score: $F\ (1,29) = 132$, $p < .001$, $\eta_p^2 = .820$; see Figure 2).[1] The second GLM confirmed that when participants made an error, the distance between the chosen drawer and the correct drawer was smaller during EL (displacement score: $F\ (1,29) = 22.5$, $p < .001$, $\eta_p^2 = .437$).

The Marascuilo procedure showed that the proportions of errors were lower for EL than for the "errorless" item of the three measures, since each absolute difference was greater than the critical values (*ps* < 0.05; see Figure 3 and a complete overview of results in the Supplement), indicating that the memory performance was better during mere EL than when "errorless" items were mixed with "trial and error" items during the TEL condition.

Figure 3. The *K* proportion of errors for the errorless block and the "errorless items" of the trial-and-error block.

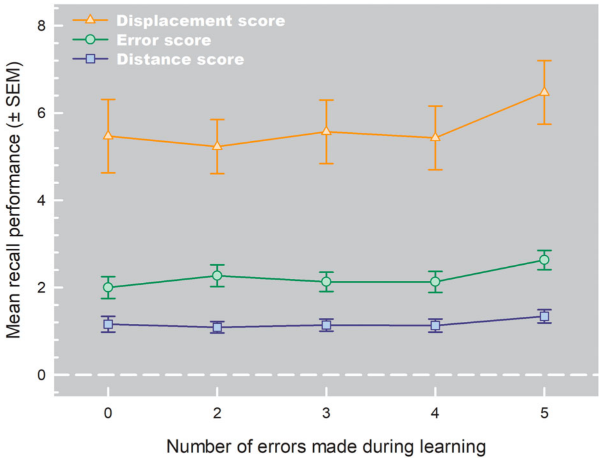

Figure 4. The error score, displacement score and distance score and standard error of the mean for the trial-and-error trial types for the different numbers of errors that were made.

The results of the third GLM testing for the effects of error frequency (performance on the 0, 2, 3, 4 and 5 error trials) on the TEL recall using the three measures showed no significant effects (error score: $F(3.47,101) = 1.75$, $p = .153$, $\eta_p^2 = .057$; displacement score: $F(3.72,108) = .649$, $p = .617$, $\eta_p^2 = .022$; distance score: $F(3.65,106) = .679$, $p = .595$, $\eta_p^2 = .023$; see Figure 4).[2] Likewise, no significant effect was found when comparing the trials (0 vs. 2 errors, 0 vs. 3 errors, etc.) on the error score (*p*-values > .105), displacement score (*p*-values > .848) and distance score (*p*-values > .837; for a complete overview of the results see Supplement), pointing out that the amount of errors encountered during the acquisition phase had no influence on performance. Note that for the error score, the difference in performance was slightly bigger for TEL for the 5 vs. 0 contrast compared to the other comparisons to the zero-errors condition, although this effect was not significant ($p = .162$).

Discussion

Our results support the notion that recall of previously acquired object-location associations is superior after a strictly EL condition – in which no errors could occur – compared to a TEL condition in which the number of errors made during learning was pre-set (varying from 0 to 5). Moreover, the errors made during the acquisition phase of TEL interfered with the performance on the "errorless" items in this condition. The findings also showed that when an error had occurred during TEL, the distance between the incorrect recalled object location and the correct location was larger. However, the number of errors made during TEL did not affect performance during recall. That is, in this study the accuracy of recall depended on whether or not a person committed an error during the acquisition phase, and not the amount of errors made during learning.

These results contradict the Desirable Difficulties hypothesis (Bjork, 1994; Schmidt & Bjork, 1992), but are in line with previous reports of better recall from memory in healthy young participants due to EL. For example, Heldmann et al. (2008) demonstrated that performance on a word-fragment completion task was better after EL than after TEL in healthy young adults. Moreover, Kessels, Feijen, et al. (2005) found an EL advantage using a spatial memory task in young adults, whereas older adults did not differ in performance on EL and TEL. For face-name associations, Kessels and De Haan (2003) also reported a larger beneficial effect of EL in young adults compared to older adults. Furthermore, Haslam, Moss, and Hodder (2010) showed that healthy participants performed better during mere EL and during EL in combination with vanishing cues relative to TEL when participants just had to learn object-surname associations or when they had to learn object-surname associations and simultaneously monitor the number of taps on their hands. Based on the EL and TEL findings obtained in healthy young and older adults, Cyr and Anderson (2018b) concluded that TEL may be preferred for flexible and conceptual, meaning-based, information regardless of age, whereas EL may be preferred for inflexible and non-conceptual information irrespective of age or memory impairment, such as in our Drawer Task.

The beneficial effect of EL and the finding that the errors made during learning interfered with the "errorless" items of TEL condition suggest that stored errors conflict with correct memory traces during retrieval of information. This competition was prevented during EL, facilitating the memory performance, showing a similar response to EL in healthy young adults as in older adults and patient populations. Furthermore, based on the Hebbian learning principles (Hebb, 1949) it can be expected that the co-activation of neurons involved in processing errors and memory targets increases the strength of the coupling between the errors and the targets. This makes it likely that the neuronal ensembles will become active together during the retrieval of information, irrespective of the correctness of the response. Because of this, the outcome of this process must be checked for accuracy by an error-monitoring system which can distinguish errors from targets and can apply corrections if necessary. From this perspective, it is possible that our participants were still monitoring and correcting for errors while the next object was already being presented. This could have reduced processing resources for the following, "errorless" item during TEL condition, ultimately resulting in a worse memory performance.

Unexpectedly, the number of errors made was unrelated to the learning outcome in the TEL condition in our sample of high-functioning young adults. This finding converges with those obtained by Bridger and Mecklinger (2014), who noticed that the frequency of the occurrence of errors during testing did not influence the EL advantage observed in a word stem completion task, and by Rodríquez-Fornells et al. (2004), Hammer et al. (2009) and Heldmann et al. (2008), suggesting that the error frequency did not influence the strength of the engagement of the error-monitoring system. A possible explanation is that the significance of errors devaluated after the first error occurred during the acquisition phase, as the occurrence of errors are less surprising and therefore the second, third, fourth or fifth error could have been less meaningful to them. In accordance with this explanation, several studies found a relation between ERN amplitudes and error significance (Gehring et al., 1993; Hajcak, Moser, Yeung, & Simons, 2005; Hester et al., 2008; Maier & Steinhauser, 2016) and the likelihood of errors by showing that each single error is less surprising when the error frequency is relatively high (Brown & Braver, 2005; Castellar, Kühn, Fias, & Notebaert, 2010; Fischer, Klein, & Ullsperger, 2017). Moreover, an fMRI study by Hester, Madeley, Murphy, and Mattingley (2009) found increased pMFC activity for initial errors that were corrected relative to repeated errors during a Go/No-go response inhibition task in which participants were given the opportunity to learn from their errors. This, combined with the inclusion of only healthy individuals that should have a well-functioning error-monitoring system, could be a plausible explanation for why performance was not affected by error frequency in this sample.

It is also noteworthy that although no significant effect was found for error frequency, the difference in performance on the error score was slightly bigger for objects that had to be memorised after 5 errors during TEL. This could indicate that recall from memory is not affected by the frequency of errors in healthy young adults when the number of errors is relatively low, but that the effects of error frequency may only become evident when a high amount of errors are occurred. This notion would be in line with Maier and Steinhauser's (2017) findings that working memory load did not affect error detection per se, but that the evaluation of error significance decreased as working memory load increased with complexity, which could have affected subsequent consolidation into long-term memory. Also, as memory capacity and learning ability decline with ageing (Park, 2000), it can be expected that the amount of errors has a more profound influence on memory performance in older adults. A similar prediction can be made for clinical populations that show impairments in memory and error-monitoring, such as mild cognitive impairment or mild-to-moderate dementia (Bettcher, Giovannetti, Macmullen, & Libon, 2008), traumatic brain injury (Bertens et al., 2016) or Korsakoff's syndrome (Rensen et al., 2017, 2019). Future research should examine whether the error-monitoring system is able to apply corrections by using the Drawer Task in individuals with an impaired error-monitoring system.

One potential limitation of the present paradigm is that the number of trials was relatively low for the TEL condition, with only 4 trials per error frequency. Therefore, it cannot be ruled out that including a larger amount of trials per error frequency would have allowed for the detection of an effect of error frequency during TEL. Moreover, it would be preferable for the EL and TEL condition to be more similar with respect to duration and, perhaps, including an unexpected recall phase.

In conclusion, our newly developed paradigm, the Drawer Task, enables the systematic manipulation of the number of errors made during learning object-location associations and is a valid task to examine learning and recall under EL and TEL conditions. The task allows for more accurate comparisons and analyses due to the automated design and greater control over the error frequency compared to previously used laboratory tasks in the field of EL (see Haslam & Kessels, 2018). Understanding the underlying mechanisms of EL, notably the impact of error frequency on learning and the relation between error-monitoring ability, executive control processes and overall cognitive function on learning outcome, can potentially contribute to exploring differences in people's learning ability and style. Future research should, therefore, explore the predictors of the positive EL effects in ageing and different clinical populations using the Drawer Task, for instance in patients with mild cognitive impairment or traumatic brain injury.

Notes

1. Due to the unmet assumption of normality, a Wilcoxon signed-rank test with the same independent and dependent variables was additionally conducted, which confirmed this effect (error score: $z = -4.71$, $p < .001$; displacement score: $z = -4.41$, $p < .001$; distance score: $z = -4.78$, $p < .001$).
2. On account of the unmet assumption of normality, Friedman's nonparametric test was as well computed with the same variables and certified this effect (error score: $\chi^2(4) = 7.31$, $p = .121$; displacement score: $\chi^2(4) = 1.31$, $p = .860$; distance score: $\chi^2(4) = .667$, $p = .955$).

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