

# Repeated encoding fosters retention of perceptual detail in visual recognition memory

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In a 2014 issue of *Learning & Memory*, Reagh and Yassa proposed that repeated encoding leads to semanticization and loss of perceptual detail in memory. We presented object images one or three times and tested recognition of targets and corresponding similar lures. Correct lure rejections after one in comparison to three exposures were more frequently associated with corresponding target misses, suggesting that higher lure rejections after one exposure reflect memory failure rather than perceptual fidelity. Signal detection theory analysis showed that three exposures improved lure-old discriminations. Thus, repeated encoding fosters rather than hinders retention of perceptual detail in visual recognition memory.

Throughout life, many events repeat themselves, such as commutes, coffee breaks, birthdays, and family visits. It can be challenging to differentiate repeating events in memory, as reflected in source misattributions and memory distortions (e.g., Kim et al. 2012, 2019; Sievers et al. 2019). At the same time, we are able to retrieve separate instances of repeating events, an ability that is assumed to reflect pattern separation processes in the hippocampus that prevent interference by recruiting distinct neural patterns to establish orthogonal memory representations for overlapping inputs (O'Reilly and McClelland 1994; Yassa and Stark 2011). Kirwan and Stark (2007) developed the Mnemonic Similarity Task (MST) as a tool to behaviorally assess pattern separation processes (for review, see Stark et al. 2019). In this task, subjects are asked to differentiate previously encoded stimuli from perceptually similar and novel stimuli in a yes/no recognition task, with the assumption that lure-old discriminations are based on detailed representations of old stimuli, whereas novel-old discriminations require only gist-like representations. Using this task, Reagh and Yassa (2014) showed that repeated encoding enhances target recognition but, surprisingly, also impairs similar lure discrimination. The authors explain this counterintuitive finding with the Competitive Trace Theory (CTT) (Yassa and Reagh 2013). According to CTT, item repetition establishes similar but nonidentical memory traces. With repetition, the overlapping trace elements become strengthened and gist-extracted, enhancing novel-old discriminations, whereas the nonoverlapping contextual elements start to compete with one another, causing trace interference and impaired lure-old discriminations.

Loiotile and Courtney (2015) (see also Zhang and Hupbach 2019) replicated this finding when using the lure discrimination index (LDI) by Reagh and Yassa (2014). However, when applying signal detection theory (SDT), they found that repeated exposure improved both novel-old and lure-old discrimination. SDT takes differences in memory strength between lures and old stimuli into account whereas the LDI considers lure strength only, such that small differences in lure correct rejection rates are not calibrated against stark differences in target strength between one and three repetitions. Thus, depending on which analysis method is used, vastly different conclusions are reached about the impact of encoding frequency on memory precision. Separate from these analytical considerations and of theoretical importance is the question of why repeated encoding increases false alarm rates in the first

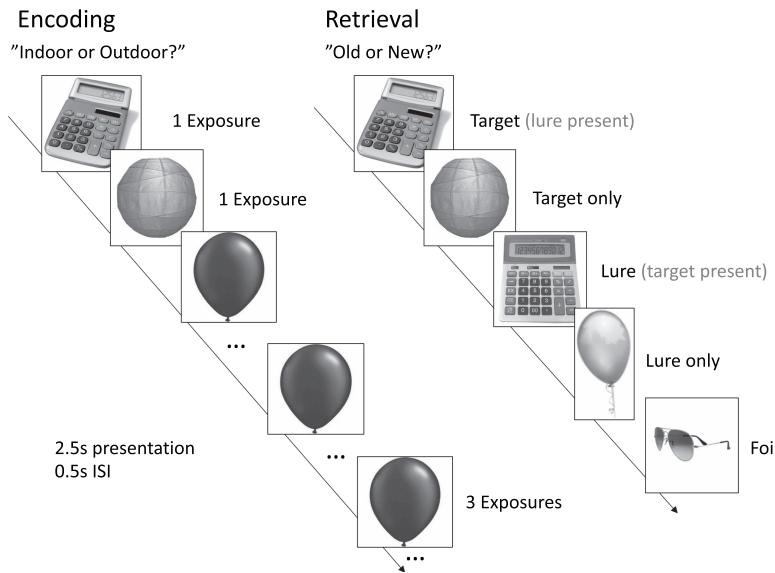
place. Similar lures can be correctly rejected for two very different reasons (Loiotile and Courtney 2015): (1) The lure triggers recall of the target, and differences between the retrieved target details and lure details are noticed ("recall-to-reject"-strategy) (see also Kirwan and Stark 2007), or (2) the resemblance of the lure to the target is missed, because the target is only weakly represented or forgotten, and therefore, the lure is perceived as an entirely new item. Repeated encoding strengthens target memory, and therefore, the majority of correct rejections in the repeated encoding condition should be based on reason 1. However, single-trial encoding is associated with weaker target strength, and therefore, increased lure rejection rates could reflect increased forgetting (reason 2), instead of better detail memory (reason 1). The paradigm used by Reagh and Yassa (2014) cannot differentiate between these two possibilities, because for each encoded image, either the target or the lure is presented during recognition. Thus, it is unclear whether targets could have been recognized for rejected corresponding lures.

To overcome this limitation and to specify the mechanisms for lure rejection after single versus repeated encoding, a new condition was created in which both targets (e.g., the calculator that was encoded) and their corresponding lures (e.g., a different calculator, see Fig. 1) were presented for recognition. This allowed us to assess whether lure rejections were based on successful vs. failed target retrieval. In a first experiment, encoding and recognition were administered within a single experimental session, as in previous studies. In a second experiment, we implemented a 24-h delay between encoding and recognition to test whether accelerated semanticization of repeated items requires a prolonged consolidation period. Thirty-eight undergraduates (seven males,  $M = 20.3$  yr of age,  $SD = 2.0$ ) from Lehigh University participated in Experiment 1 after providing informed consent. The study was approved by Lehigh's Institutional Review Board. During the first phase, participants incidentally encoded 192 images of common objects (from <https://faculty.sites.uci.edu/starklab/mnemonic-similarity-task-mst/>) for 2.5 sec each (0.5-sec interstimulus interval) while performing an indoor/outdoor judgment task. Half of the images were viewed once (one-repeat), and half were seen three times (three-repeat), resulting in 384 total trials. The order of

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**Figure 1.** Schematic of the experimental design. Participants incidentally encoded images of common objects once or three times while performing “Indoor/Outdoor” judgments. In the old/new recognition task, images of the same objects (targets), images of similar but not identical objects (lures) and images of new objects (foils) were presented. For half of the encoded images, both targets and corresponding lures were presented, and for the other half, either targets or corresponding lures were presented. After each old/new judgment, participants provided confidence ratings.

presentation was pseudorandomized such that items repeated three times were not presented consecutively. In an old/new recognition task, for half of the images both targets and their corresponding lures were presented (48 one-repeat and 48 three-repeat targets and their corresponding lures, for a total of 192 trials), and for the other half, either the targets or corresponding lures were presented (24 one-repeat targets, 24 one-repeat lures, 24 three-repeat targets, 24 three-repeat lures). Lures were drawn from two similarity bins and equally assigned to the repeat/correspondence conditions. Of all lure items, half were from bin 2, which is more similar to the original target and half were from bin 3, which are more distinctive (see Reagh and Yassa 2014). In addition, 96 novel foil images were presented. Targets, lures and foil stimuli were presented randomly throughout the recognition test with the restriction that the lag between targets and corresponding lures was at least five items. Participants were asked whether an image was “old” or “new.” They were explicitly told “old” referred to

exactly the same image that they had seen earlier and “new” referred to an item that they had not seen within the context of this study. Following each judgment, they were asked to rate their confidence from “not at all sure” to “somewhat sure” to “very sure.” The experimental procedure is illustrated in Figure 1.

Table 1 shows proportions of target hits, correct lure rejections, and modified LDIs (see below) for corresponding and noncorresponding items in each repetition condition. For corresponding items, the proportion of hits when corresponding lures were correctly rejected is also displayed.

First, we assessed novel-old discrimination by analyzing  $d'$  scores [ $d' = z(\text{“old”}) - z(\text{“old”|novel})$ ] with a repeated measures ANOVA with repetition and target-lure correspondence as fixed factors. Repeated encoding improved novel-old discrimination,  $F_{(1,37)} = 148.84$ ,  $P < 0.001$ ,  $\eta_p^2 = 0.80$ . No other effects were significant,  $F \leq 1.08$ ,  $P \geq 0.30$ . Following Loitile and Courtney (2015), we also measured novel-old discrimination using SDT. For this analysis, confidence ratings

were converted to five cumulative confidence bins. For each participant and repetition condition, these bins were used to fit receiver operator characteristic (ROC) and z-transformed ROC curves, plotting hit rates for targets against false alarm rates for novel items, using the RscorePlus algorithm (Harvey 2013). The slopes and intercepts extracted from these curves were used to calculate  $d_a (= \sqrt{2}/(1 + zROC \text{ slope}^2) \times zROC \text{ intercept})$ , which captures the distance between novel and target stimuli and reflects a participant’s discriminative sensitivity. Analysis of  $d_a$  showed that repetition improved participants’ ability to discriminate targets from novel stimuli,  $t_{(37)} = 11.62$ ,  $P < 0.001$ , Cohen’s  $d = 1.89$ . Both analysis methods confirm prior reports of repetition benefitting target recognition (Reagh and Yassa 2014; Loitile and Courtney 2015).

Second, we assessed lure-old discrimination by calculating a modified LDI that calibrates lure correct rejections on target miss rates in each repetition condition, for example,  $LDI_{1\text{-repeat}} = p(\text{“new”|lure})_{1\text{-repeat}} - p(\text{“new”|old})_{1\text{-repeat}}$ . A repeated-measures

**Table 1.** Hits and correct rejection rates and lure discrimination indices after one or three repetitions for the corresponding and noncorresponding condition

	Noncorresponding		Corresponding	
	One-repeat	Three-repeat	One-repeat	Three-repeat
Experiment 1				
Hit	0.74 (0.11)	0.90 (0.08)	0.72 (0.13)	0.89 (0.07)
Correct rejection	0.60 (0.13)	0.55 (0.19)	0.57 (0.13)	0.56 (0.18)
LDI	0.34 (0.16)	0.45 (0.19)	0.29 (0.16)	0.46 (0.20)
Hit/CR	—	—	0.67 (0.18)	0.88 (0.10)
Experiment 2 (24-h delay)				
Hit	0.50 (0.19)	0.83 (0.09)	0.53 (0.16)	0.80 (0.11)
Correct rejection	0.73 (0.14)	0.55 (0.16)	0.67 (0.12)	0.62 (0.14)
LDI	0.23 (0.15)	0.38 (0.15)	0.20 (0.14)	0.42 (0.16)
Hit/CR	—	—	0.51 (0.20)	0.79 (0.14)

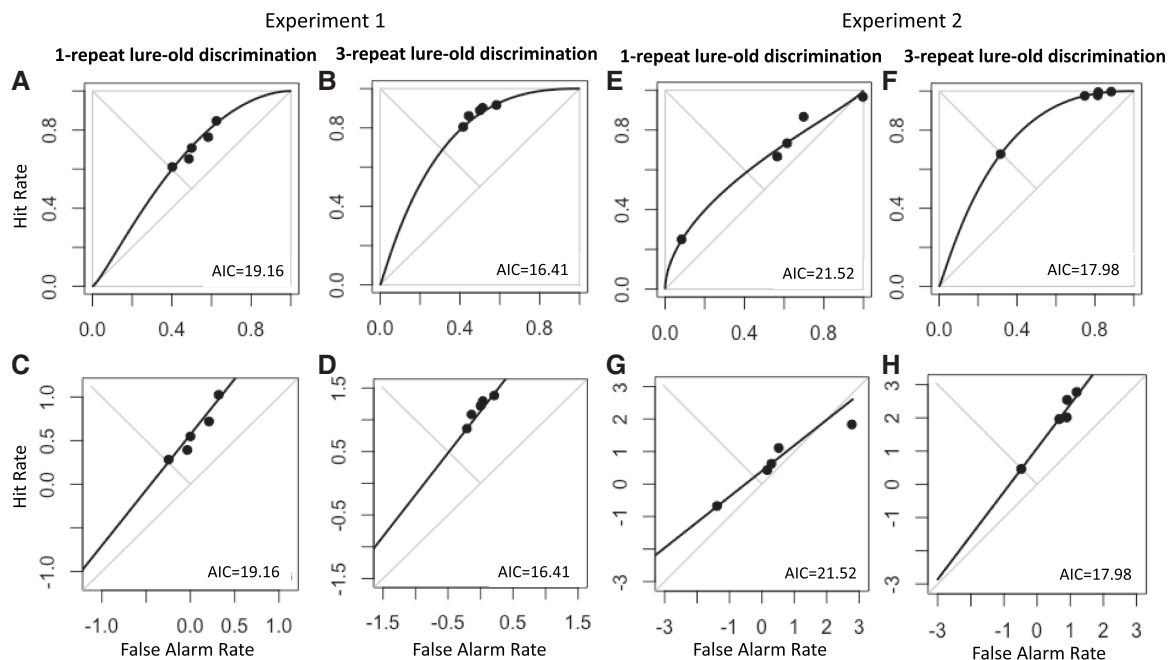
In the noncorresponding condition, either targets or lures were presented during test. In the corresponding condition, for each item, both the target (e.g., the calculator that had been encoded) and the lure (e.g., a different calculator) were presented. For the corresponding condition, proportion of target hits for correctly rejected corresponding lures are displayed. Standard deviations are shown in parentheses.

ANOVA with repetition and target-lure correspondence as factors revealed a significant effect of repetition,  $F_{(1,37)} = 48.78$ ,  $P < 0.001$ ,  $\eta_p^2 = 0.57$ , no main effect of correspondence,  $F_{(1,37)} = 2.02$ ,  $P = 0.16$ , but a significant interaction between repetition and target-lure correspondence,  $F_{(1,37)} = 4.28$ ,  $P = 0.046$ ,  $\eta_p^2 = 0.10$ . Repeated exposures improved lure-old discrimination. The presentation of corresponding targets impaired participant's ability to reject similar lures in the one-repeat but not in the three-repeat condition. In both conditions, targets likely recovered gist information (Barry et al. 2019; McCormick et al. 2020), however, follow-up elaboration of episodic details that were needed to differentiate targets from lures failed more frequently in the one- than three-repeat condition. Additionally, for each participant and repetition condition, we fitted ROC and zROC curves, plotting hit rates for targets against false alarm rates for lures (see Fig. 2). Analysis of  $d_a$  showed that repeated encoding enhanced lure-old discrimination,  $t_{(37)} = 7.41$ ,  $P < 0.001$ , Cohen's  $d = 1.20$ . These results directly contradict the finding by Reagh and Yassa (2014) of impaired lure discrimination after repeated exposures but confirm the results of Loitile and Courtney (2015) that were obtained when analyzing lure-old discrimination with SDT.

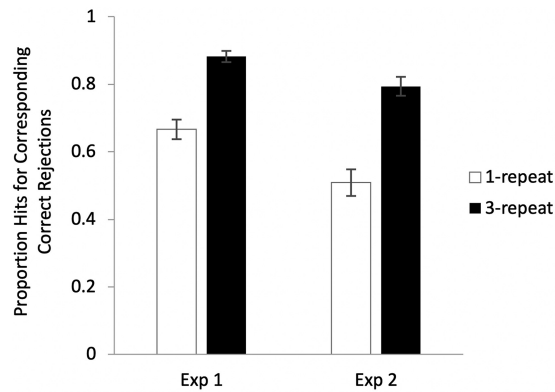
Critically, the presentation of both targets and their corresponding lures allowed us to explore the basis for correct rejections after varying repetitions. For the corresponding condition, we analyzed the proportion of hits when corresponding lures were correctly rejected to see if participants could recognize the old stimulus when correctly rejecting the lure (see Fig. 3). We also considered whether the target or lure of a corresponding pair was presented first. One participant was excluded from this analysis because of zero correct rejections in one condition. A repetition  $\times$  order repeated-measures ANOVA revealed overall reduced hit rates when targets were presented after lures,  $F_{(1,36)} = 8.24$ ,  $P < 0.05$ ,  $\eta_p^2 = 0.19$ . Rejecting a similar lure might introduce uncertainty or an increased tendency to subsequently reject all items of a kind (see Sabia et al. 2017 for a similar finding). Importantly, cor-

rect rejections were associated with higher hit rates in the three-compared with the one-repeat condition,  $F_{(1,36)} = 87.29$ ,  $P < 0.05$ ,  $\eta_p^2 = 0.71$ , and this effect did not interact with presentation order ( $F < 1$ ). This means that after one exposure, correct lure rejections were more frequently associated with memory failures; targets whose corresponding lures were correctly rejected were missed on average 33% in the one-repeat, but only 12% in the three-repeat condition. Thus, the previously reported (small) advantage in correct rejection rates after one exposure cannot be taken as evidence that target details were preserved in memory. This finding challenges the assumption of the CTT that reencoding fosters the creation of semanticized memory representations that lack episodic detail.

Although CTT assumes that semanticization is dependent on the frequency of reactivation/reencoding rather than the passage of time per se, we reasoned that repeated encoding might merely trigger a semanticization process that then plays out over a prolonged consolidation period. Therefore, in a second experiment, we added a 24-h delay between encoding and test, allowing memory traces to consolidate. Because we expected the delay to decrease memory accuracy overall, we selected lures from bin 3 only because images in this bin are more dissimilar from one another. Additionally, the number of items was reduced to 160 items, of which half were presented once, and half presented three times. As in Experiment 1, in the old/new recognition test, for half of the items in each repeat condition, both target and corresponding lures, and for the other half, either targets or lures were presented. Twenty-seven Lehigh University Students participated in this study. One participant was excluded due to foil false alarm rates exceeding 0.5, leaving 26 participants for analysis (12 males,  $M = 21.4$ ,  $SD = 3.0$ ). Because Experiment 2's sample was more balanced than Experiment 1 in terms of gender distribution, we included gender as a factor in the ANOVAs of  $d'$  and modified LDI. Female participants showed marginally better target memory than male participants [ $d'$ ;  $F_{(1,24)} = 4.18$ ,  $P = 0.052$ ,  $\eta_p^2 = 0.15$ ], consistent



**Figure 2.** Lure-old ROC and zROC curves for the one-repeat (Exp. 1: A,C; Exp. 2: E,G) and three-repeat conditions (Exp. 1: B,D; Exp. 2: F,H). The black curves/lines represent the fitted SDT model, averaged across all participants. The ROC (zROC) data points are cumulative proportions (z-scored cumulative proportions) of each response type—for example, “very sure old”—for lure and old stimuli, across all participants. The increased distance of the three-repeat points (and models) from the line  $y = x$  is evidence for better discrimination between lure and old stimuli in the three-repeat condition.



**Figure 3.** Proportion of target hits when corresponding lures were correctly rejected in Experiments 1 and 2.

with the results of a recent meta-analysis showing a female advantage for memory of nameable images (Asperholm et al. 2019). No gender differences were observed for lure discrimination [modified LDI;  $F < 1$ ]. Gender did not significantly interact with any other factors, neither in the  $d'$  nor the LDI analysis ( $F \leq 2.97$ ;  $p \geq .10$ ). Replicating Experiment 1, repetition enhanced both target memory [ $d'$ ;  $F_{(1,24)} = 208.45$ ,  $P < 0.001$ ,  $\eta_p^2 = 0.90$ ] and lure discrimination [modified LDI;  $F_{(1,24)} = 44.85$ ,  $P < 0.001$ ,  $\eta_p^2 = 0.65$ ], independent of target-lure correspondence (repetition  $\times$  correspondence interactions,  $F \leq 2.74$ ;  $P \geq 0.11$ ). This was confirmed by SDT analysis ( $d_a$ ); repetition enhanced both novel-old discrimination,  $t_{(25)} = 12.47$ ,  $P < 0.001$ , Cohen's  $d = 2.45$ , and lure-old discrimination,  $t_{(25)} = 9.51$ ,  $P < 0.001$ , Cohen's  $d = 1.86$ . In the corresponding condition, hit rates for targets whose corresponding lures were correctly rejected were affected by presentation order,  $F_{(1,25)} = 6.95$ ,  $P = 0.014$ ,  $\eta_p^2 = 0.22$ , and repetition  $F_{(1,25)} = 111.04$ ,  $P < 0.001$ ,  $\eta_p^2 = 0.82$ , but these factors did not interact,  $F_{(1,25)} = 1.42$ ,  $P = 0.25$ . Replicating Experiment 1, hit rates were smaller when targets were presented after lures and importantly, correct lure rejections were more frequently associated with target hits in the three-than one-repeat condition. Specifically, after a 24-h delay, correct lure rejections were associated with 49% misses in the one-repeat, but only 21% misses in the three-repeat condition, suggesting that after one exposure, lures were frequently rejected because participants could not remember the item altogether. Thus, Experiment 2 shows that repetition even in combination with a longer consolidation period does not impair similar lure discrimination. Instead, repeated encoding fosters retention of perceptual detail in visual recognition memory. As in Experiment 1, lure rejections after one exposure were associated with higher target misses, suggesting that higher lure rejection rates in this condition reflect poorer encoding and higher rates of memory loss. This finding directly challenges the conclusion of Reagh and Yassa (2014) that one exposure is associated with higher memory fidelity.

CTT assumes that reencoding of an event or item establishes a new memory trace that is similar but not identical to the original trace. With every repetition, nonoverlapping elements that are unique to each encoding event compete with one another for neocortical representation and begin to degrade, whereas overlapping elements become strengthened (Yassa and Reagh 2013), causing a gradual transformation of memory from episodic to semantic. Applied to visual recognition, Reagh and Yassa (2014) posit that although repeated encoding strengthens the knowledge that a particular item was encoded (e.g., "I saw a phone") it impairs recollection of the specific instance of that item (e.g., "I saw *this* phone"). We argue that this reasoning does not follow logically from CTT, because the specific perceptual item features repeat

across encoding events and thus constitute overlapping elements that should be strengthened and retrieved with high fidelity, consistent with the current findings and those of Loitile and Courtney (2015).

A limitation of our study and the one by Reagh and Yassa (2014) is that items were repeated under identical encoding conditions. According to the CTT, pattern separation processes in the hippocampus drive competitive interference in the neocortex. However, item repetition has been found to elicit pattern completion rather than pattern separation processes (Bakker et al. 2008; Pidgeon and Morcom 2016). Therefore, greater contextual variability during encoding might be needed to induce competition. We are currently exploring whether more varied encoding conditions impair target-lure discrimination at test.

Our study examined the basis for correct lure rejections after one and three exposures. We conclude that one time encoding leads to weaker memory traces such that similar lures are more frequently rejected not because targets are well remembered, but because targets are forgotten. Our finding that repeated encoding preserves perceptual details and counteracts semanticization suggests that item reexposure has fundamentally different consequences than spontaneous reactivation that often occurs during sleep and supports the development of a gist-like memory version that does not require the hippocampus for retrieval (e.g., Inostroza and Born 2013). Similarly, Sekeres et al. (2016) showed that reminders and active retrieval prevent the loss of details in episodic memory. Additionally, reexperiencing an event in its original context can reinstate hippocampus dependency and memory specificity (Winocur et al. 2009). Our findings are compatible with the memory transformation theory that assumes that detailed hippocampus-dependent memories can coexist and dynamically interplay with more schematic generalized variants that depend on neocortical structures (Sekeres et al. 2018).

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