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BRIEF REPORT

Contextual familiarity rescues the cost of switching

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Abstract
Changes in context influence the way we form and structure memories. Yet, little is known about how qualitatively different types of context switches shape memory organization. The current experiments characterize how different features of context change influence the structure and organization of free recall. Participants completed a context switching paradigm in which we manipulated the rate of switches and prior experience with the contexts participants were switching between (repeated vs. novel). We measured free-recall performance and determined the extent to which participants organized items by the order in which they were encoded or the type of context with which they were originally presented. Across two experiments, we found and replicated that rapidly switching to novel, but not repeated contexts, impaired memory recall performance and biased memory towards a greater reliance on temporal information. Critically, we observed that these differences in performance may be due to distinctions in how participants organize their recalls when rapidly switching contexts. Results indicated that participants were less likely to only cluster their responses by the same context when the contexts were repeating at a high rate, as compared to when the contexts were novel. Overall, our findings support a model in which contextual familiarity rescues the costs associated with rapidly switching to new tasks or contexts.

Keywords Context switching · Free recall · Frequency · Novelty · Episodic memory

Introduction

Our environment is ever-changing, filled with switches in context varying in how often switches occur as well as prior exposure to the contexts (i.e., relative novelty). These types of changes profoundly influence how we form and structure memories. For instance, imagine watching a movie in the living room while preparing dinner in the kitchen. If asked to recall what happened in the movie, your later memory of a specific scene may become associated with memories of preparing dinner, supporting the recall of those memories. Instead, you could run errands in a new shopping mall. You may have difficulty recalling all the items purchased since you were rapidly switching between each new store. Prior research showed how memory performance is influenced by several different qualia of context, including perceptual attributes (Heusser et al., 2018), task set (Polyn et al., 2009b), and stimulus class (DuBrow & Davachi, 2013, 2016). Questions remain about how the qualitative features of context change influence memory structure and organization.

There are two particular features of contextual change known to influence memory but that have yet to be studied in the context of free recall: rate of context changes and relative novelty of the context to which one is switching. Typically, when an item is presented during study, it is stamped into a continuously drifting context representation. The detection of a sufficiently novel representation, however, can cause a sudden shift in context (Polyn et al., 2009a). When slowly alternating between different contexts, the internal context that tags individual items is highly differentiated, which has been shown to provide structure for participants' free recall (Heusser et al., 2018; Polyn et al., 2009b). However, when rapidly switching between two repeated contexts, part of the prior context may not only linger into the new context at transitions, but also overlap, creating a "blended" contextual representation. Little is known about whether a "blended" internal context representation would be beneficial or detrimental for free-recall memory.

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One possibility is that recall accuracy would benefit from rapid contextual switching as items will be more easily recalled if tagged with more varied contexts, providing more contextual retrieval cues (Lohnas et al., 2011; Siegel & Kahana, 2014). However, recall could also be impaired due to interference from overlapping memories that share similar internal context representations. When memories share features, retrieving those memories may be more difficult compared to memories that do not share features due to heightened competition during retrieval (Anderson, 2003). The current set of experiments was designed to arbitrate between these two hypotheses.

The factors that contribute to a "blended" context may not solely rely on the frequency of switching, but could also be modulated by the learner's familiarity with the contexts. Accumulating evidence suggests that salient events, like encountering a novel scene (Zacks & Swallow, 2007) or oddball items (Ranganath & Rainer, 2003; Von Restorff, 1933), can separate the overlap amongst two contexts and boost memory performance. However, increasing the amount of novelty or frequency of novel events leads to worse memory performance (Radvansky et al., 2011; Reggev et al., 2018; Shepherdson, 2021) and less access to information immediately following the shift (Dux & Marois, 2009). These findings lead us to expect that recall memory would be impaired specifically when individuals are rapidly switching to novel versus repeated events due to less access to retrieval cues.

One mechanism by which switch rate may influence recall performance is by inducing competition during memory search between items learned with contexts that are switching versus not switching. With a limited time to recall, the most memorable items will "win." When an item "wins" this competition, the context representation is updated and the next item recalled will likely have been encoded with a similar context (Lohnas et al., 2015; Lohnas & Kahana, 2014; Polyn et al., 2009a). A related, yet parallel question will investigate whether the presence of competition during memory search (competitive vs. pure lists) differentially influences memory performance when switching contexts at different rates.

This present study uses a context switching paradigm in which we independently manipulate switching rate and relative novelty of the contexts. We sought to characterize how these qualitatively different features of context change influence how well items are remembered and organized. We predict that memory will be differentially affected by switch rate with exposure to novel contexts, such that rapidly switching to novel contexts will be more harmful for memory compared to slower switching as participants may have less access to retrieval cues. We also predict that returning to a repeated context may independently benefit memory as a "blended" context could provide more contextual retrieval cues. We then determine the extent to which items are organized by the order in which they were encoded or the type of context with which they were originally presented.

Experiment 1

Method

Participants

One hundred and ten participants from the University of Oregon completed this experiment online for course credit. One participant was excluded for chance-level performance on the encoding task, 19 participants were excluded for failing to provide audio usable for verbal recall, and six participants were excluded for writing down words as indicated on a post-experiment questionnaire. The final sample size for analysis was 84 participants (65 female, mean age 19.46 ± 3.17 SD years). Participants were randomly assigned to one of two contextual familiarity groups (repeated = 41; novel = 43). Sample size was determined based on standards in the literature of free recall (e.g., Polyn et al., 2009a) and doubled given that this study has a between-subjects manipulation. Consent was obtained in a manner approved by University of Oregon's Institutional Review Board.

Stimuli

In brief, encoding consisted of alternating presentations of word and scene stimuli. Scene stimuli consisted of 46 unique scene contexts, where half depicted an indoor scene and half depicted an outdoor scene (Chang et al., 2019). A scene context is defined as the image immediately preceding a particular study item (word). We randomized the presentation of scene contexts appearing in each condition across participants. Cue words were 240 two-syllable nouns presented in capitalized letters (e.g., "GIRAFFE"). Nouns were based on object image labels from the Bank of Standardized Stimuli (Brodeur et al., 2014). Words were randomly assigned to scenes and conditions uniquely for each participant. Stimuli were presented using Inquisit 6 [computer software]. (2020). Retrieved from https://www.millisecond.com.

Procedure

After a brief practice, the experiment consisted of eight lists, with each list consisting of three sequential phases: encoding, distractor, and recall (Fig. 1a). On each trial, participants viewed a scene context for 1,000 ms. The scene disappeared for 500 ms and was then followed by a word presented in the center of the screen for 2,500 ms. Alternating presentations of scene and word stimuli were chosen as it has previously been shown as an effective way to manipulate

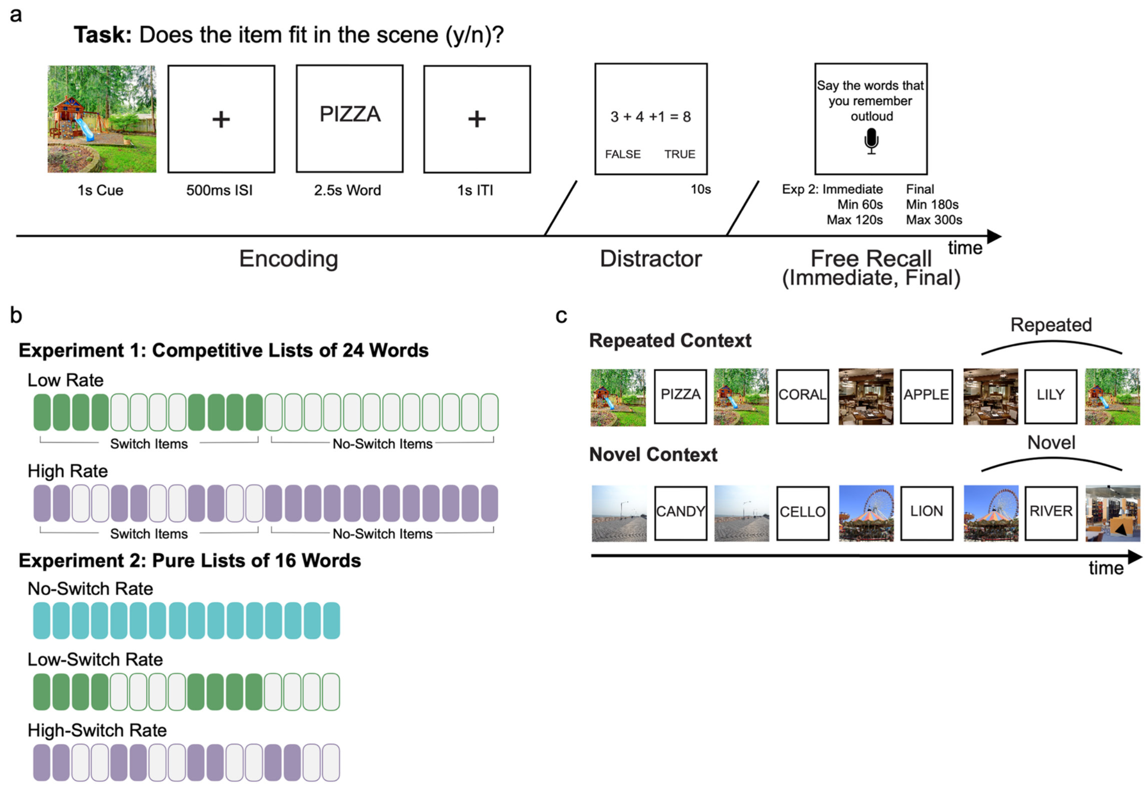

Fig. 1 Task design for Experiments 1 and 2. **a** Procedure. Each trial began with the encoding phase, which consisted of alternating presentations of word and scene stimuli. Participants were instructed to respond as to whether the item depicted by the word would fit in the scene. After a 10s distractor task, participants verbally recalled as many items as possible from the list that they could. After all eight lists were completed, participants completed a final recall. **b** Within-Subjects Switch Rate Manipulation. In Experiment 1, participants learned lists with a high or low contextual switch rate. These were competitive lists with two switch types per list (switch vs. no-switch). In Experiment 2, participants learned pure lists at just one switch rate (no vs. low vs. high). Participants in Experiment 1 learned lists of 24 words, whereas participants in Experiment 2 learned lists of 16 words. **c** Between-Subjects Contextual Familiarity Manipulation. We manipulated the level of contextual familiarity with the scene contexts (repeated vs. novel)

temporal context (Chan et al., 2017; Manning et al., 2016). During the word presentation, participants were instructed to respond as to whether the item depicted by the word would fit in the previous scene (yes/no). This is a subjective judgment as to whether the participant could picture a given item in the scene previously presented, which did not contain the item. The word remained on the screen for 2,500 ms regardless of a button press to equate encoding time. Trials were separated by a 1,000-ms intertrial interval (ITI), which consisted of a blank screen. Each list in the encoding phase included a total of 24 words.

Immediately following each encoding phase, participants completed a math distractor task to reduce rehearsal. Participants were presented with math equations in the form of A + B + C = D, where the values of A, B, and C were set to single digit integers (Howard & Kahana, 1999). Participants were instructed to indicate whether the statement was true or false with a key press. The distractor phase lasted 10 s in total, but the number of equations completed was variable depending on speed of completion.

After the distraction period, participants were given up to 3 min to verbally recall as many items as possible from the list that they could, without any explicit instructions about the order of the of recall. A written cue indicated the start of the recall period, and participants' microphones were turned on for recording. Participants could move onto the next list whenever they felt that they recalled as many words as they could remember. After all eight lists were completed, participants moved onto the final recall portion of the experiment. Participants were instructed to verbally recall as many words as they could from the entire experiment for up to 3 min.

Design

The encoding task contained two main conditions of interest. For the first condition of interest, we manipulated the switch rate between scenes to generate two switch rates within subjects: low rate and high rate (Fig. 1b). For the low rate, the scene contexts changed after every four items. The high rate was the most rapid switch rate, where the scene context switched after every two items. Each list had two different switch types within the list: switch (high or low) and no-switch (Fig. 1b). The no-switch rate (baseline) is the slowest switch rate, where all of the items were studied with the same scene (no context switches). The rationale was to create competitive lists and to include a baseline, no-switch rate for comparison within each list. Therefore, given that a list was composed of 24 unique items, 12 are presented at the no-switch rate and 12 are presented at the switch rate (either the low-switch or high-switch rate). List order and switch type order was randomized for each participant.

The second condition of interest is the level of contextual familiarity that participants have with the scene contexts. We manipulated contextual familiarity (repeated vs. novel) as a between-subjects variable (Fig. 1c). Within a given list in the repeated context condition, participants switched back and forth between the same two scene contexts (see Fig. 1b for example list). In other words, when there was a change in the scene context, it would be a repeat of a scene that had already been seen in the list previously. However, in the novel context condition, each time there was a switch in scene context, participants would see a novel scene that had not been seen before in the experiment. In both groups, every list contained new scenes and included both switch and no-switch items.

Data analysis

Statistical analyses were conducted in R 3.6.3 (R Core Team (2020); https://www.R-project.org/). For the encoding task, given the subjectivity of responses, accuracy was calculated based on normative responses. We determined whether each response matched the modal response for when each word was presented with each scene. Mean responses were calculated for each level of contextual familiarity and compared using Welch's Two-Sample t-tests, as there are unequal sample sizes. Effect sizes (e.g., Cohen's d) were calculated using the *lsr* package in R.

Using the *lme4* package in R, generalized linear mixed-effects models were used to determine whether switch rate (low vs. high), switch type (no-switch vs. switch), and contextual familiarity (repeated vs. novel) predicted the percent of words that participants recalled, with subject and word identity as random effects. Specifically, we ran a model that assessed the relationship between percent of words recalled and the interaction between switch rate, switch type, and contextual familiarity. In a parallel question, we were interested in how the nature of competition between switch rates during memory search influences memory performance. Therefore, we ran an additional model that further unpacked the two-way interaction between switch rate and switch type. Given that our main predictions were about the high-switch rate, we ran a third model that specifically looked at the two-way interaction between high-switch rate and contextual familiarity (repeated vs. novel) to better interpret this interaction. These analyses were run for both immediate and final recall data (see Online Supplementary Material (OSM) Fig. 1 for final recall results). Additionally, we ran a final model to determine whether item position in the event predicted the percent of words that participants recalled (see OSM Analysis 1). All models additionally controlled for list number and list half (whether the word appeared in the first 12 or last 12 items in the list) as fixed effects.

To determine the extent to which participants tend to successively recall nearby items, we calculated a temporal clustering score for each participant (Polyn et al., 2009a). For each recall transition, we determined the temporal distance (in absolute lag) between the serial position of the just-recalled word and the set of not-yet-recalled words. The temporal clustering score is calculated as the proportion of possible lags greater than the observed lag. A score of 1 indicates high temporal clustering, meaning that participants made the shortest transitions possible. A score of 0.5 indicates chance-level temporal clustering, meaning that transitions were just as likely to be to a neighboring or remote item. For this analysis, each participant received two temporal clustering scores: one for high-rate lists (which includes both the switch and no-switch items) and one for low-rate lists (which includes both the switch and no-switch items). Temporal clustering scores were computed using publicly available MATLAB (The MathWorks, Natick, MA, USA) scripts from the Behavioral Toolbox (Version 1.01) from the Computational Memory Lab (http://memory.psych.upenn.edu/Behavioral_toolbox). Mean temporal clustering scores were calculated and compared across levels of contextual familiarity (repeated vs. novel) using t-tests.

Verbal recall responses were digitally recorded and annotated offline using Penn Total Recall (http://memory.psych.upenn.edu/TotalRecall). Four undergraduate research assistants, who were blind to which words were randomly assigned to which switch rate and level of contextual familiarity (repeated vs. novel), annotated the verbal responses. A recall was classified as valid if the item recalled came from the current list. Items from previous lists, words not in the wordpool, or other vocalizations (e.g., "umm") were not included in analysis.

Results

Encoding performance

Overall accuracy was 87.71%. Accuracy and response time (RT) did not differ for repeated and novel context switches (Accuracy: repeated- M = 87.72%, SE = 0.96, novel- M = 87.71%, SE = 0.9, $t(81.42) = 0.01$, $p = .99$, $d = .002$; RT: $F(1, 82) = 1.42$, $p = .24$, $d = .11$).

Context switching and immediate recall performance

Participants recalled 22.37% of total words. Free-recall accuracy was greater for repeated (24.45%) versus novel (20.39%) switches, $t(81.99) = 2.18$, $p = .03$, $d = .48$, suggesting that participants' memory was better for words from lists containing repeated scenes.

We next examined whether switch rate, switch type, and contextual familiarity influenced recall performance. There was a significant three-way interaction, highlighting that the relationship between switch rate (high vs. low) and switch type (no-switch vs. switch) differed depending on whether scenes were repeating or novel, $z = -2.48$, $p = .01$, partial $R^2 < .001$ (see OSM Table 1 for full model).

Next, we unpacked the two-way interaction between switch rate and switch type. With exposure to novel contexts, recall performance was reduced when switching contexts at a high rate, compared to not switching, $z = 3.26$, $p = .001$, partial $R^2 = .003$ (Fig. 2a). There was no detriment to memory for low-switch, compared to no-switch, items with novel context switching, $z = .30$, $p = .76$, partial $R^2 = .001$. This resulted in a reliable high × low rate interaction, which highlights that performance is disrupted only when switching to novel contexts at a high rate, $z = 2.05$, $p = .04$, partial $R^2 < .001$. Interestingly, there was a boost in recall performance for high-switch, over no-switch, items when switching back to repeated contexts, $z = 2.83$, $p = .005$, partial $R^2 = .001$ (Fig. 2a).

Given that performance differences were specific to rapid switching, a final analysis was conducted to directly test the interaction between high-switch rate and contextual familiarity. This resulted in a reliable high rate × context familiarity interaction, $z = 4.21$, $p < .001$, partial $R^2 = .002$ (Fig. 2a). This means that switching back to repeated contexts at a rapid rate may rescue the cost associated with rapidly switching to novel contexts.

Context switching and recall organization

We next investigated how switch rate and contextual familiarity influenced temporal organization. Results showed that both switch rates across both levels of familiarity showed significant binding of items to their temporal context, as measured by greater than chance-level temporal clustering (*ps* < .001). However, when individuals were switching to novel versus repeated contexts, there was a greater reliance on temporal information (i.e., higher temporal clustering), $t(157.6) = 4.99$, $p < .001$, $d = .77$ (Fig. 2b).

Experiment 1: Discussion

The results suggest that costs to memory only occur when individuals are rapidly switching to novel contexts. In fact, participants' memory performance was improved when rapidly switching to repeated contexts over not switching. This suggests not only a benefit for switching to repeated contexts, but that impairments of switching to novel environments only emerged in the context of rapid versus slower switches.

Experiment 1 used competitive lists (containing both switch and no-switch items) to test how competition between switch and no-switch items during memory search influenced memory performance. Results demonstrated that this competition shaped memory performance. First, performance for no-switch items differed depending on switch rate (high vs. low), given that no-switch items were competing with different switching rates in memory. Additionally, memory differences between switch and no-switch items were only observed in high-switch rate lists. For Experiment 2, we investigate whether competition between switch rates was necessary to observe memory differences.

We additionally found that switching to novel contexts was more likely to increase reliance on temporal

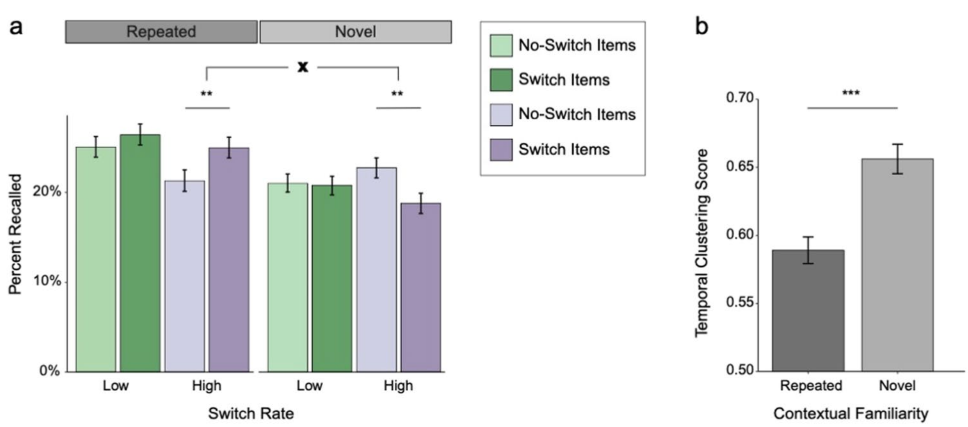

Fig. 2 **a** Immediate recall performance. **b** Temporal clustering. Error bars reflect within subject standard error. ** $p < .01$, *** $p < .001$

information. This may seem counterintuitive as recall performance is disrupted at a high switch rate to novel contexts, supporting the idea that participants may be making more remote transitions when switching to repeated contexts. These findings support the framework that when scenes are repeatedly encountered, a "blended" context representation is created that spans the entire list, supporting long-distance transitions. We quantitatively test this in Experiment 2 by further investigating the types of recall transitions made by participants.

Experiment 2

Experiment 2 aimed to replicate the above findings with increased sample size and recall performance. The goals for Experiment 2 were: (1) replicate the recall performance findings that the negative effect of switching on memory recall was rescued (at least as good as not switching) when switching to a repeated context, and (2) replicate and expand on the recall organization results to further investigate how participants structure their memory. To expand, we investigated the types of recall transitions participants made.

Method

Participants

One hundred ninety-two native English speakers were recruited from Prolific. In order to increase power for Experiment 2, we doubled the sample size from Experiment 1. Participants were compensated an initial \$6.50 and could receive an additional bonus payment of up to \$6.00 for good performance on the encoding and recall portions of the experiment. Nine participants were excluded for chance-level performance on the encoding task, six participants were excluded for failing to provide audio usable for verbal recall, and ten participants were excluded for writing down words as indicated on a post-experiment questionnaire. The final sample size for analysis was 167 participants (90 female, mean age 35.74 ± 12.98 SD years). Participants were randomly assigned to one of two context switching groups (repeated = 83; novel = 84). Consent was obtained in a manner approved by University of Oregon's Institutional Review Board.

Stimuli

The stimuli used for Experiment 2 were the same as those used in Experiment 1. However, in Experiment 2, we only used 30 of the scene contexts as the list length was shortened (see below).

Design and procedure

The procedure for Experiment 2 was identical to that of Experiment 1, except for the following changes aimed at improving participants' verbal recall performance. The first set of changes were made to the encoding portion of the experiment. First, the list length was shortened to only contain 16 items per list. The rationale for this change was to help improve recall performance. Second, given that the lists were shorter, the switch rate variable changed such that there are now three distinct switch rates (no-switch, low-switch, and high-switch) presented in their own list to optimize the number of switch items per condition. Thus, participants learned pure lists where there was no competition between switch rates during memory search as each rate was learned and tested separately. This allowed for investigating whether competition is necessary for observing differences in recall performance between switch rates as no competition is present in Experiment 2. Additionally, this eliminated the switch type variable. Participants saw two lists of each switch rate for a total of six lists. One additional change was made in the instructions to improve the clarity of the encoding task and create a more even distribution of yes/no responses. Participants were completing the same encoding task as Experiment 1, but were now instructed to make a yes/no judgment as to whether they could find the item in the scene.

We also changed the recall portion of the experiment. In Experiment 1, participants could move onto the next list whenever they felt that they recalled as many words as they could remember. However, in Experiment 2, a minimum time was added to the immediate and final recall. The instructions were changed to encourage participants to continue to search their memory until at least the minimum time was up. After the minimum time was up, participants could move onto the next list, or continue to search their memory until the maximum time has passed. For immediate recall, participants had up to two minutes to recall, but would not be allowed to continue until after one minute. For final recall, participants had up to 5 min to recall, but would not be allowed to continue until after three minutes. This change was aimed at increasing recall performance by preventing participants from recalling just a few words and moving on and rather encouraging them to really search their memory.

Data analysis

Data analysis was identical to Experiment 1 with the following changes and additions. First, given that Experiment 2 used pure lists, the switch type variable is eliminated from analyses. Therefore, generalized linear mixed-effects models were used to determine whether switch rate (no-switch vs. low-switch vs. high-switch) and contextual familiarity (repeated vs. novel) predicted the percent of words that participants recalled, with subject and word identity as random effects. Specifically, we ran a model that assessed the relationship between percent of words recalled and the interaction between switch rate and context familiarity. As in Experiment 1, these analyses were run for both immediate and final recall data (see OSM Fig. 1 for final recall results), and all models additionally controlled for list number and list half as fixed effects.

Additionally, we sought to determine the extent to which participants successively recalled items shown with the same scene, or source context. During the encoding task, items (represented by words) were paired with the scene context immediately preceding. We were interested in the question: When a participant makes a local transition during recall, how often is it to the same or a neighboring context? There are three types of local transitions. Same context transitions were when participants made their next recall to an item paired with the same context as the context of the just-recalled item. Backward context transitions were when participants made their next recall to an item paired with the context immediately preceding (backwards) the context of the just-recalled item. Lastly, forward context transitions were when participants made their next recall to the item paired with context immediately following (forwards) the context of the just-recalled item. Only local transitions were analyzed as this is a fair comparison between switching to repeated vs. novel contexts (see OSM Analysis 2 for further investigation into local and remote transitions). Inclusion of remote transitions would allow participants switching to repeated contexts to transition between items paired with the same scene throughout in the list, which was not possible when switching to novel contexts. Therefore, inclusion of only local transitions allowed for an analysis of the same types of transitions for lists with repeated and novel contexts.

For this analysis, we calculated the conditional response probabilities by local context type, similar to (Polyn et al., 2009a). For each participant, we tallied the number of recall transitions that were between items studied with the same image, the previous image (backwards transition), and the following image (forwards transition). We then conducted two different analyses: (1) To account for differences in the number of transitions each participant made, we divided each context type by each participant's total number of recall transitions. This gave the proportion of local transitions for each participant that was then averaged across all participants in each group (see OSM Fig. 2). 2) Separately, to account for the fact that there were a different number of opportunities to transition to each context type (same, forward, or backward), the number of recalls from each type was divided by the total number of recall transitions possible for that type. This gave the probability of local transitions for each participant that was then averaged across all participants per type.

Here, we were interested in how organization by source context differed between repeated and novel context switches, within each switch rate. Therefore, we used the *lme4* package in R to run Linear Mixed-Effects Models to make such comparisons. The high-switch and low-switch rates had a different number of items between each transition (two vs. four items), so therefore it would not make sense to compare these two rates, as the number of potential switch transitions differs across rates. Thus, we ran two separate models, one for the low-switch rate comparing repeated vs. novel context switches and one for the high-switch rate again comparing repeated versus novel context switches. Additionally, this analysis was unable to be run in Experiment 1 because within a given list, recalls included items from both a no-switch and a switching (low-switch or high-switch) rate. Therefore, transitions between items are not matched.

Results

Encoding performance

Overall accuracy was 85.3%. Accuracy and RT did not differ between repeated and novel switches (Accuracy: repeated- M = 84.61%, SE = 0.94, novel- M = 85.99%, SE = 0.64, $t(158.27) = 1.13$, $p = .26$, $d = .17$; RT: $F(1, 165) = 1.47$, $p = .23$, $d = .09$).

Context switching and immediate recall performance

Participants recalled 50.47% of total words. There were no differences in the percent of words recalled between repeated (51.15%) and novel (49.79%) switches, $t(164.97) = .51$, $p = .61$, $d = .08$. This demonstrates that design changes made in Experiment 2 were successful in raising recall performance and equating overall accuracy across levels of contextual familiarity.

We next tested for interactive effects of switch rate (no-switch vs. low-switch vs. high-switch) and contextual familiarity (repeated vs. novel). Replicating Experiment 1, rapidly switching to novel, $z = -2.64$, $p = .008$, partial $R^2 = .001$, but not repeated, contexts reduced memory performance and resulted in a reliable interaction, $z = 2.19$, $p = .03$, partial $R^2 = .001$ (Fig. 3). There were no performance differences for low-switch between repeated and novel contexts, $z = .07$, $p = .94$, partial $R^2 < .001$. As expected, recall performance when not switching was similar between novel and repeated contexts, $z = -.003$, $p = .99$, partial $R^2 = .001$, since there was no competition between rates in memory search. Thus, we directly replicated that memory recall is hindered *only* when switching to novel contexts at a high rate.

Context switching and recall organization

Temporal clustering Results showed that all switch rates across both levels of contextual familiarity exhibited greater than chance-level temporal clustering (ps < .001).

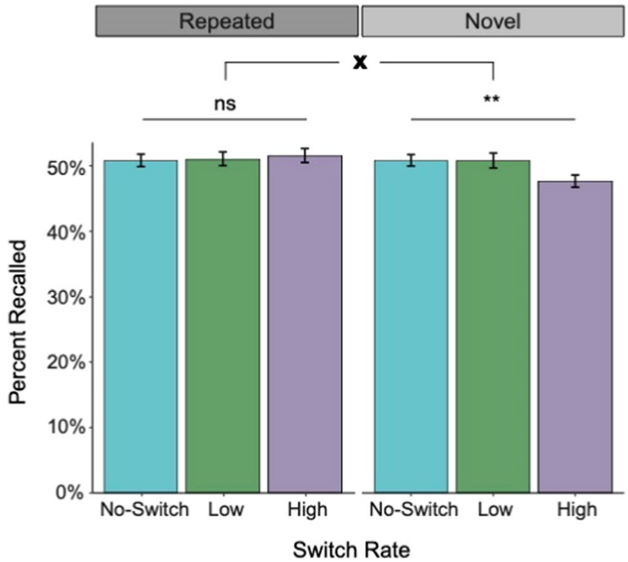

Fig. 3 Immediate recall performance. Error bars reflect across subject standard error. ns $p > .05$, ** $p < .01$

Replicating results from Experiment 1, there was greater reliance on temporal information (i.e., higher temporal clustering) when switching to novel, compared to repeated, contexts, $t(330.14) = 3.07$, $p = .002$, $d = .34$ (Fig. 4a).

Recall transitions by context One reason that performance differences were specific to switching at a high rate may be differences in how participants organized their memory. Therefore, this next analysis examined the proportion of recall transitions made to the same or neighboring contexts (forwards or backwards). At the high-switch rate, participants transitioned significantly more to items in the same context compared to neighboring contexts when switching to repeated, (Forwards: $t(164.0) = 3.03$, $p = .002$, partial $R^2 = .029$, Backwards: $t(164.00) = 5.33$, $p < .001$, partial $R^2 = .085$) and novel (Forwards: $t(166.0) = 7.87$, $p < .001$, partial $R^2 = .177$, Backwards: $t(166.0) = 9.17$, $p < .001$, partial $R^2 = .226$) contexts. Although all participants made most of their recall transitions to the same context, there was a significant interaction such that there was less of a difference in the probability of making same vs. forward, $t(330.0) = 3.503$, $p < .001$, partial $R^2 = .020$, or same vs. backward, $t(330.0) = 2.83$, $p = .004$, partial $R^2 = .013$, context transitions when participants were switching to repeated, compared to novel, contexts (Fig. 4b). This demonstrates a notable difference in how participants switching between repeated vs. novel contexts organize their recalls when switching at a high rate.

For the low-switch rate, participants transitioned significantly more to items in the same context compared to neighboring contexts in repeated, (Forwards: $t(246) = 6.85$, $p < .001$, partial $R^2 = .163$, Backwards: $t(246) = 7.13$, $p < .001$, partial $R^2 = .174$), and novel contexts, (Forwards: $t(249) = 9.68$, $p < .001$ partial $R^2 = .277$, Backwards: $t(249) = 9.90$, $p < .001$, partial $R^2 = .287$; Fig. 4b). There were no significant differences between repeated and novel switches.

Experiment 2: Discussion

Replicating Experiment 1, results demonstrated that memory was hindered only when switching to novel contexts at a

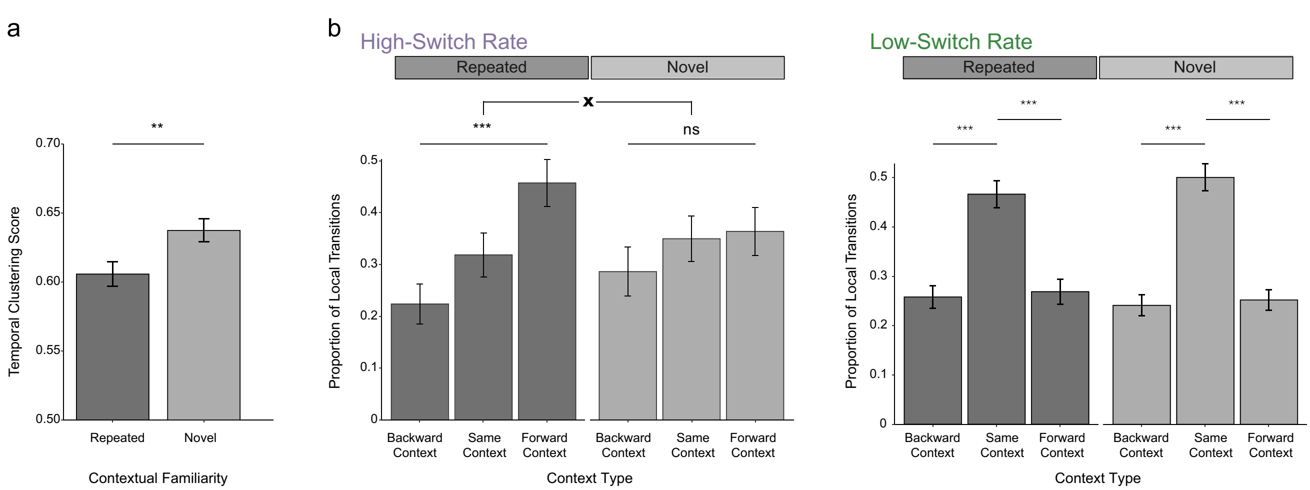

Fig. 4 **a** Temporal clustering. **b** Probability of local recall transitions by context for high-switch (left) and low-switch (right) rates. Here we calculated the probability of making a local transition compared to the number of possible transitions per type. The low-switch and high-switch results are unable to be directly compared due to differences in the number of items between each transition (two vs. four items). The main comparison of interest is between repeated and novel context switches within switch rates. Error bars reflect across subject standard error. ** $p < .01$, *** $p < .001$

high rate, highlighting a unique function of rapid switching on memory performance. Additionally, although there was no direct memory benefit, memory for items during repeated context switches was just as good as memory with no context switches, reducing the costs associating with rapidly switching to novel contexts.

Experiment 2 used pure lists (no competition between switch and no-switch items) to test whether competition was necessary to see differences in memory performance between switch rates, as in Experiment 1. First, as there was no boost in memory performance for either the high-switch or the low-switch rates above the no-switch rate for repeated context switches, this suggests that competition between switch and no-switch items during memory search is an important component for boosting switch items in memory. However, replicating Experiment 1, rapidly switching to novel contexts hindered memory performance, compared to not switching, suggesting that regardless of list composition, rapidly switching to novel contexts is harmful for memory recall performance.

General discussion

Across two experiments, we investigated free-recall performance and organization after manipulating the rate and familiarity of context switches. Consistent with our hypothesis, we found and replicated that memory was differentially affected by switch rate with exposure to novel contexts, where there was a recall detriment only when switching at a rapid rate. However, this detriment was not observed when participants switched rapidly between repeated contexts, suggesting that rapidly switching between repeated contexts may rescue the cost associated with rapidly switching to novel contexts. We also found that relative novelty of the contexts shaped recall organization. Participants who switched to novel contexts relied more heavily on temporal information. On the other hand, when participants rapidly switched to repeated contexts, they were less likely to only cluster their responses by the same context.

The results of both experiments add to a growing body of literature characterizing the effects of switching contexts on free-recall performance and organization. Previous studies found that a single change in task set (Polyn et al., 2009b) or slowly changing perceptual features (Heusser et al., 2018) during learning are sufficient to impose structure on free recall, where more transitions were made between items studied using the same task compared to different tasks. Our findings from the low-switch rate are consistent with this result. We extend to suggest that clustering by scene context may be switch rate dependent. Specifically, participants are less likely to only cluster their responses by context during rapid switching to repeated, compared to novel, contexts. Our results also replicate previous findings that participants tend to recall information in a similar temporal order in which it was learned. We extend these findings by showing that temporal clustering is heightened during novel context switching. In certain situations, clustering items by their temporal context may not be as adaptive, where participants may have more success grouping items by contextual, semantic, or motivational relationships between items (Horwath et al., 2023; Howard & Kahana, 2002a, b; Polyn et al., 2009a). However, in situations when such relational information may be unavailable or changing too quickly, participants may rely more on remembering the items in their studied order.

Importantly, and adding to prior work on novelty and memory, we demonstrate that the cost of switching to novel events is specific to switching at a high rate. This is consistent with previous work where increasing the amount of novelty leads to worse memory performance (Radvansky et al., 2011; Reggev et al., 2018; Shepherdson, 2021). Here, participants may become overloaded with new, quickly changing information which influences their ability to remember specific items. For instance, research suggests that novelty-related context disruption may reduce accessibility for items studied prior to the novel events (Polyn et al., 2009a). However, the detriment was eliminated when participants slowly changed to new information. An open question for future work is to understand why slowly switching to novel contexts does not hinder free recall. The findings from the present experiments highlight the importance of the rate at which individuals switch to novel environments. Moreover, the number of switches per list may also be relevant for disrupting memory. Future research should further disentangle how the number versus rate of context switches influences memory.

Our findings also support a clear memory distinction between switching to repeated vs. novel contexts. Across both experiments, we found a cost for switching to novel contexts at a high frequency that was not present when switching to repeated contexts. In fact, memory performance after rapidly switching between repeated contexts was just as good as not switching. This suggests that rapidly switching to repeated contexts may rescue the costs of rapidly switching to novel contexts. A similar result was found in previous work, where participants demonstrated worse memory for an item they were carrying if they walked through multiple novel rooms compared to returning back to the same room (Radvansky et al., 2011). Here, we provide novel evidence for this memory effect after multiple switches using a free-recall paradigm.

One explanation for these differences in recall performance may be due to effects of context change. Context plays an important role in guiding free recall, where the success of memory search is a function of the overlap between contextual representations at test and contextual features during encoding (Godden & Baddeley, 1975; Howard & Kahana, 2002a, b; Smith et al., 1978; Smith & Vela, 2001). Therefore, one possibility is that novel context switches create a larger mismatch in contextual representations between encoding and test, given the greater number of scene changes. This is supported by evidence suggesting that a change in mental context impairs recall of the list prior to the context change, given that the prior list no longer matches the test context, but benefits memory for the following list that better matches the test context (Delaney et al., 2010; Mulji & Bodner, 2010; Sahakyan et al., 2013; Sahakyan & Kelley, 2002). The current findings and interpretations shed additional light for why some context change manipulations impair vs. improve recall performance.

Lastly, results demonstrated that when participants were rapidly switching to repeated contexts, the likelihood of recalling the next item from the same context relative to the likelihood of recalling an item from a neighboring context is more similar than when participants were switching to novel contexts. Thus, when participants switch to repeated, compared to novel, contexts, they were less likely to recall their next item from the same context. Therefore, the next item a participant recalls is more likely to come from neighboring contexts when switching to repeated, compared to novel, contexts. Despite these items being paired with two different external contexts, this would suggest that they are encoded with a similar, "blended" internal context representation, given that individuals are more likely to successively recall items encoded with a similar context representation (Polyn et al., 2009a). As expected, a "blended" representation is specific to repeated contexts, as there is less of a cost for thinking about the first context into the second context. During continuous switching, the first and second contexts are both active and can be used to access memories for unique items. Alternatively, having many contexts continuously active could lead to interference during novel context switches. Moreover, previous research using a similar analysis to the present study found that in lists with a single task switch, participants were more likely to recall their next item from the same task (Polyn et al., 2009a), suggesting that this framework is specific for context switching at a higher frequency. The present results begin to suggest that creating a "blended" context representation may serve as a better retrieval cue with repeated contexts compared to contexts with high amounts of novelty. Future working using neuroimaging techniques can better understand internal context representations during rapid context switching and how that influences memory structure and performance.

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Declarations

Ethics approval Approval was obtained from the ethics committee of University of Oregon. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Not applicable.

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Open practices statement The data and custom analysis scripts for the current article are available upon request to the corresponding author (L.I.R.). None of the experiments were preregistered.