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Self-Reported attention to changes and associations with episodic memory updating

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ABSTRACT

Successfully navigating changing environments requires updating memories. The present experimental and individual differences study examined associations between attention while encoding changes and subsequent memory updating. Participants studied word pairs with responses that changed from first (A-B) to more recent (A-D) appearances. Participants were intermittently probed about their attentional state, with "on task" indicating attentive study, and then attempted to recall responses and if the responses changed. Within- and between-subject associations between task reports and recall were highly consistent. On-task reports for A-D pairs were positively associated with recent-response (D) recalls when participants were on task for A-B pairs. Additionally, on-task reports for A-B pairs were positively associated with first-response (B) recalls only when participants were on task for A-D pairs. Finally, first- (B) and recent-response (D) recalls were positively associated. These correlational findings are consistent with the causal proposal that attention to A-D pairs enables retrieval of A-B pairs during study, which presents opportunities for associative encoding that counteracts proactive interference.

Introduction

In educational settings, students are often tasked with assignments that require extended focused attention, such as listening to a lecture or reading a story. An instructor may tell their class to use the next 10 min to read a short story for later discussion, assuming that students will focus diligently on the reading. Unfortunately, this is unlikely for the whole 10 min, despite honest effort from the students. Anticipation of an exciting afterschool activity, the sound of another student tapping a pencil against their desk, or even the perceived difficulty of the reading may cause a student's focus to lapse and their mind to wander. Such lapses may cause students to miss vital pieces of information, like a relationship between two characters or a clue about the identity of a villain, leading to confusion or frustration when tested on the material.

As a reader progresses through a story, they create a model of the text that is constantly updated as they continue to read, adding in details and filling in unknowns. Although stories progress from beginning to end in a cohesive manner, and a reader may be able to guess the outcome of an event based on their existing model of the text, there are features that, when encoded, change the model over time. For example, a character that appeared at first to be loyal ended up betraying a friend, causing one to update one's model of the story to change the character from "hero" to "villain." One way to remember more recent events in the text as such is to detect how episodes changed from the past, such as when one notices that a character's current behavior differs from their previous behavior. This updating of episodic memory can guide future behaviors, such as correctly identifying the story's villain on a later test.

Episodic memory updating that is accomplished by noticing and remembering changes requires people to attend to distinctive features of each episode. However, sustaining attention is effortful. People often disengage attention from the external world and reallocate it to internal thoughts (Smallwood & Schooler, 2015). This mind wandering occurs more often over time and for people who struggle to sustain their attention. While attention to a stimulus usually leads to better memory, mind wandering while experiencing more recent events with similar but not identical features may lead to interference. The degree of this

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disruption may also vary with how well people can focus their attention on the features of external material instead of internal thoughts. These issues may be addressed using paired associate learning tasks that precisely control changes in associations across presentations. The present experiment used this approach to examine associations between self-reported attention during encoding of specific events and subsequent memory. This study also examined individual differences in such attention and their associations with memory for changes in the features of earlier and more recent events.

Episodic memory updating and memory for changes

Episodic memory updating has been operationalized as various consequences of encoding related information across occasions. In the reconsolidation literature, updating refers to how reactivated memories are modified by subsequent events (for reviews, see Elsey et al., 2018; Lee et al., 2017). In the directed forgetting literature, updating refers to how disregarding outdated information before studying new information reduces the accessibility of outdated information and reduces proactive interference effects on memory for recent information (for reviews, see Bjork, 1978; Sahakyan et al., 2013). Relatedly, studies from the classic interference literature show that changing the physical location of study episodes can improve memory for recent information by creating more distinctive representations (for a review, see Smith & Vela, 2001). Finally, updating in the memory integration literature refers to how features of recent events cue retrieval of existing memories and allow both events to become associatively encoded with the order of their occurrence (for reviews see, Schlichting & Preston, 2015; Wahlheim et al., 2021). Here, we focus on the role of the accessibility of earlier event memories in the extent to which those memories interfere, or create opportunities for integration, with memories of recent events.

On the surface, interference and integration views may appear at odds, but there is evidence that they are two sides of the same coin. Conditions that presumably improve the noticing of relationships between existing memories and current perceptions may promote interference (Kuhl et al., 2012). However, noticing such relationships can also promote episodic memory updating when such relationships can be later recollected. Early evidence for the enhancing effects of noticing relationships was shown using an A-B, A-D protocol (Postman & Gray, 1977). Participants learned A-B pairs in List 1 and A-D pairs in List 2. While learning A-D pairs, participants either recalled D responses without referencing A-B pairs or recalled B and D responses. Contrary to the interference view, which would have predicted poorer memory for D responses when participants practiced retrieving B and D responses during List 2 learning, such retrieval practice improved D response recall and source memory for both responses on a later test. These results are reminiscent of work showing that bringing to awareness any relationships between existing memories and current perceptions can counteract retroactive interference (Bruce & Weaver, 1973; Robbins & Bray, 1974). Others have proposed that doing so promoted study-phase retrievals of first responses (B) while studying A-D pairs (Benjamin & Ross, 2010). This possibility is also consistent with recursive remindings accounts of order memory proposing that study-phase retrievals allow people to encode and remember that recent events reminded them of earlier events (Hintzman, 2010; Tzeng & Cotton, 1980; Winograd & Soloway, 1985).

The Memory-for-Change (MFC) framework was proposed to explain the role of study-phase retrievals in episodic memory updating as shown in A-B, A-D protocols (Wahlheim & Jacoby, 2013). This descendant of the recursive reminding account proposes that co-activating A-B and A-D representations allows for B and D responses to become integrated with their order into a recursive representation. Integration of this sort can then support updating by promoting recollection-based retrieval of responses, their different list contexts, and the retrieval that led to their co-activation. However, such co-activation does not guarantee that responses will become integrated. When co-activation occurs and distinguishing features are perceived, this may also differentiate otherwise competing memories by increasing the distance between them in representational space (Favila et al., 2016; Hulbert & Norman, 2015). Although note that this differentiation mechanism has not yet been formally incorporated into the MFC framework. Alternatively, when study-phase retrievals do not stimulate mechanisms that promote updating, the associations of retrieved memories with multiple list contexts can lead to interference.

A clear demonstration of remindings in episodic memory updating using A-B, A-D tasks was shown in a study that varied the instructions to identify changed A-D pairs during study (Jacoby et al., 2015). Participants studied two lists of word pairs separated by a distractor task that separated list contexts. As in some earlier studies, List 2 included all the A-D pairs. The lag between A-B and A-D pairs varied such that some A-B pairs appeared in List 1 (at longer lags) while others appeared in List 2 before corresponding A-D pairs (at shorter lags). During List 2, participants either indicated when they noticed changes from anywhere in the experiment (i.e., Lists 1 and 2) or only in List 2. Recent-response (D) recalls from pairs that changed across lists were greater for the group who looked for changes including those from List 1 than the group who looked for changes only from List 2. Looking back to List 1 also led to better memory for the fact that responses changed. These findings suggest that improving memory for first responses (B) enabled integration with recent responses (D). Integration was also evinced by proactive facilitation in recent-response (D) recalls when changes were remembered. Although the mnemonic consequences of directed retrievals suggest that reminding promotes updating, the final test did not measure how retrieving B responses in List 2 changed the later accessibility of those responses. Later studies using A-B, A-D protocols addressed this by showing that manipulations that increased memory for changes also increased first-response (B) recalls (e.g., Kemp et al., 2023; Wahlheim et al., 2019, 2020; Wahlheim & Zacks, 2019).

Additional evidence that study-phase retrievals can mitigate interference and promote memory updating via integration has also been shown in neuroimaging studies using A-B, A-D protocols. An early example of this was shown in a study that examined retroactive interference from recent responses (D) on first-response (B) recalls (Kuhl et al., 2010). That study showed that hippocampal activation during A-D encoding that reflected retrieval of earlier-studied A-B pairs was associated with interference reduction. Later studies using similar protocols more directly examined integration as a memory enhancement mechanism by comparing activation patterns under instructions to retrieve existing memories or to retrieve memories and integrate them while learning A-D pairs (Chanales et al., 2019; Richter et al., 2016). Activation patterns classified as integration were associated with improved behavioral memory performance. More generally, these findings are consistent with findings from A-B, B-C associative inference experiments showing that reactivation of A-B pairs before or during B-C learning improves inferences about A-C associations (Schlichting & Preston, 2015; Zeithamova et al., 2012).

Collectively, these studies implicitly assume that the success of retrieving earlier memories while studying items with shared features depends on how attention was allocated both to the earlier and more recent events. Presumably, attentive study to both events is necessary for the opportunity for associative encoding but also for earlier memories to proactively interfere. Moreover, attention fluctuates over time, leading to variable encoding across study events (for a review, see Blondé et al., 2022). Such variability should therefore be associated with the success of retrieving earlier and more recent responses in A-B, A-D protocols. To motivate hypotheses about encoding variability effects on recall in A-B, A-D protocols, we next summarize select findings regarding attention and memory interactions.

Attention, mind wandering, and subsequent episodic memory

The relationship between attention during study and subsequent memory has long been established (for a review, see Long et al., 2018). It is featured prominently in studies showing that dividing attention during study impairs subsequent memory (e.g., Craik et al., 1996; Fernandes & Moscovitch, 2000). Relevant to the current paired associate learning study, divided attention costs are pronounced for associative encoding (e.g., Castel & Craik, 2003; Naveh-Benjamin et al., 2003; Troyer et al., 1999). These costs are also greater for conscious retrieval of episodic details than automatic expressions of memory, as shown in studies that estimated contributions of recollection and familiarity (e.g., Gardiner & Parkin, 1990; Jacoby, 1991; Uncapher & Rugg, 2008), compared explicit and implicit memory (e.g., Mulligan, 1997, 1998; Wolters & Prinsen, 1997), and examined reading comprehension (e.g., Smallwood et al., 2008; Steindorf et al., 2023). Collectively, these findings suggest that attentional lapses in A-B, A-D protocols should undermine noticing and later remembering of changes and associated memory outcomes.

Although attentional manipulations can control encoding conditions, they do not capture fluctuations between external stimuli and internal states that are common in daily life. Indeed, people may disengage attention from their everyday environments up to 45 % of the time (e.g., Kane et al., 2007; Killingsworth & Gilbert, 2010; McVay & Kane, 2009). To naturalistically examine attention and memory interactions, studies have assessed the relationships between self-reported mind wandering and memory (for a review, see Blondé et al., 2022). Mind wandering occurs when people shift attention away from tasks and has many operational definitions (Seli et al., 2018). In episodic memory, it refers to inattention to study items. In this way, it is akin to divided attention because it reflects the decoupling of attention from task-relevant perceptions. Consequently, like divided attention, mind wandering should undermine encoding operations that promote recollection, such as those necessary for associative encoding.

Mind wandering measured by probed reports has generally been associated with poorer encoding and episodic memory. Studies examining the consequences of encoding intention on recognition (Smallwood et al., 2003) and recall (Smallwood et al., 2004) found that mind wandering was associated with poorer memory after intentional but not unintentional encoding of real words but not non-words, suggesting that attentional lapses undermined semantic encoding. Similarly, mind wandering was associated with impaired incidental encoding that required semantic but not perceptual processing (Thomson et al., 2014), mostly for thoughts unrelated to study stimuli (Maillet et al., 2017). Mind wandering has also impaired later recollection; self-reported mind wandering was associated with lower estimated recollection from a process dissociation procedure (Smallwood et al., 2007) as well as poorer memory for the source contexts of words (Maillet & Rajah, 2014) and visual images (Blondé et al., 2022). Relatedly, mind wandering during paired associated learning, verified by less change in pupil diameter, was associated with poorer cued recall (Miller & Unsworth, 2021), which putatively relies heavily on recollection. Finally, mind wandering during text reading impaired memory for features and their integration (Smallwood et al., 2008; Steindorf et al., 2023).

Based on the aforementioned studies, the extent of attentional engagement during study should associate with the memory enhancement and/or impairment observed in A-B, A-D protocols. For enhancement, attention to A-D pairs should enable the cue specification necessary to trigger retrieval and associative encoding of A-B pairs, as well as the processing cascade that facilitates memory for responses and their relationship. This was shown in a study in which participants studied A-B pairs three times then later classified their attentional engagement on thought probes that followed A-D pairs (Garlitch & Wahlheim, 2020). On-task reports to A-D pairs—indicating self-reported, full attention during study—were associated with enhanced recent- (D) and first-response (B) recalls and that they changed. These findings suggested that full attention during A-D study promoted associative encoding. However, one limitation of that study is that it did not assess whether the associations among probe reports and recall of both responses (B and D), which implicated a role for associative encoding, depended on attention during A-B learning.

Integration accounts of memory updating predict that associations between first (B) and recent (D) responses should be more likely to develop when A-B and A-D pairs are both sufficiently attended during study. Accordingly, the improvements in recent-response (D) recalls associated with on-task reports during A-D study shown by Garlitch and Wahlheim may have occurred partly because A-B pairs were attended well enough across their three appearances. However, interference accounts predict the opposite, that recent-response (D) recalls should benefit when inattention to A-B pairs renders them a less potent source of proactive interference. Consequently, the MFC framework, which proposes roles for integration and interference, predicts that recent-response (D) recalls will benefit from attention to A-D pairs regardless of the attentional intensity that was allocated to A-B pairs. We tested these predictions here.

Individual differences in attention and episodic memory updating

The foregoing studies suggest that assessments of within-subjects relationships will illuminate the role of sustained attention during encoding in supporting other processes that determine the success of memory updating. It follows that differences in the ability to sustain attention during encoding should vary with the extent to which existing memories interfere when people perceive updated information. Here, we examined how individual variation in sustained attention associates with memory updating in an experiment that included many thought probes. This feature allowed us to estimate more precise differences in attentive study among participants than in our earlier work. We used these estimates to compute between-subjects correlations between the frequency of attentive study and recall accuracy for changed and unchanged pairs. This co-variation may provide generalizable information about who is more likely to update memories or perseverate on outdated information. Also, because we probed attention after A-B and A-D pairs, we could compute between-subjects correlations between all inter-pair report combinations and recall. This approach provides a fuller picture about how attention to earlier and more recent information relates to subsequent memory.

The role of individual differences in sustained attention in episodic memory updating is related to prior research on interference susceptibility. That work often focused on the role of executive functioning in suppressing interference from competing information (Dempster & Corkill, 1999). One prevailing view is that constructs including an attention control component can facilitate interference suppression by allowing people to focus on targeted information and avoid distractions. This is supported by findings showing that people with higher working memory capacity experience less interference in episodic memory tasks (Kane & Engle, 2000; Rosen & Engle, 1998; Unsworth, 2010; Miller & Unsworth, 2018). Relatedly, other work has shown an association between working memory and interference control factors, with the latter comprising measures from established memory tasks (Unsworth, 2019). These findings could be extended to suggest that people with better attention control can better sustain their attention during study to overcome interference. Although there is mixed evidence linking attention control and interference control (Friedman & Miyake, 2004; Stahl et al., 2014; Unsworth, 2019), sustained attention during learning has consistently been associated with better episodic memory in tasks that evoke elaborative encoding (Blondé et al., 2022), a process that is necessary for effectively encoding conflicting information. Therefore, we predict that people who sustain their attention better, which could partly reflect attention control, during the study of conflicting information will experience less interference in episodic memory updating tasks.

To further characterize this relationship, we examined the role of sustained attention in memory updating using an A-B, A-D paradigm. Our previous work showed evidence for this relationship, in that on-task reports during study of A-D pairs were positively correlated with accurate recall of both the earlier (B) and more recent (D) responses, as well as participants' ability to remember that the responses changed (Garlitch & Wahlheim, 2020). The measure of memory for changes was taken as an indication of when participants noticed changes during study and encoded those changes well enough to remember them later. However, on-task reports were not correlated with first-response (B) intrusions when recalling recent (D) responses. These findings suggest that people who sustained attention more effectively were more likely to notice changes and update their memories accordingly. In line with this possibility, work on text comprehension showed that people who never mind wandered without awareness during reading were more likely to notice and integrate clues that led to the text's antagonist than people who did (Smallwood et al., 2008). Collectively, the findings from studies of individual differences in attention and memory updating suggest that people who are on-task more often should be more likely to encode changes between earlier (A-B) and more recent (A-D) events. Conversely, people who are on-task less often should notice fewer of these relationships due to poorer encoding of earlier, recent, or both events. This pattern of results would suggest that sustained attention plays a critical role in mitigating interference, especially for people who are better at sustaining their focus while encoding conflicting information.

The present study

The present experiment examined how sustained attention during study of earlier and recent events with changed features associates with episodic memory updating. Participants studied word pairs then completed a cued recall test (see Fig. 1). During study, participants saw repeated pairs that appeared twice (A-D, A-D), control pairs that appeared once (A-D), and changed pairs that appeared with the same cue (A) paired with B then D responses (A-B, A-D). There was a considerable lag between pairs with repeated cues. Thought probes appeared after half of the A-B and corresponding A-D pairs as a measure of sustained attention during study. Participants were told to respond that they were *on task* when they had intentionally encoded the pair that had just appeared and *off task* when they had thought about anything else while the pair appeared. At test, cues appeared; participants were told to recall the D response, classify the cue based on whether it was associated with changed responses, and if so, recall the B response.

Our first two hypotheses predict that earlier-observed patterns of on-task reporting will replicate here. During study, we expect a decrease in on-task reports across trials (McVay & Kane, 2012; Teasdale et al., 1995) with an uptick when changed responses first appear (Garlitch & Wahlheim, 2020). At test, we expect overall recent-response (D) recalls for changed pairs to reflect a mixture of enhancement when participants recollect B responses and the fact that they changed, and impairment in the absence of such recollection (Wahlheim & Jacoby, 2013).

Our primary hypotheses concerning within-subjects associations between probe reports and test responses are motivated by the integration and interference views of episodic memory updating. Based on studies suggesting that integration and interference contribute to recall in A-B, A-D protocols (for a review, see Wahlheim et al., 2021), we

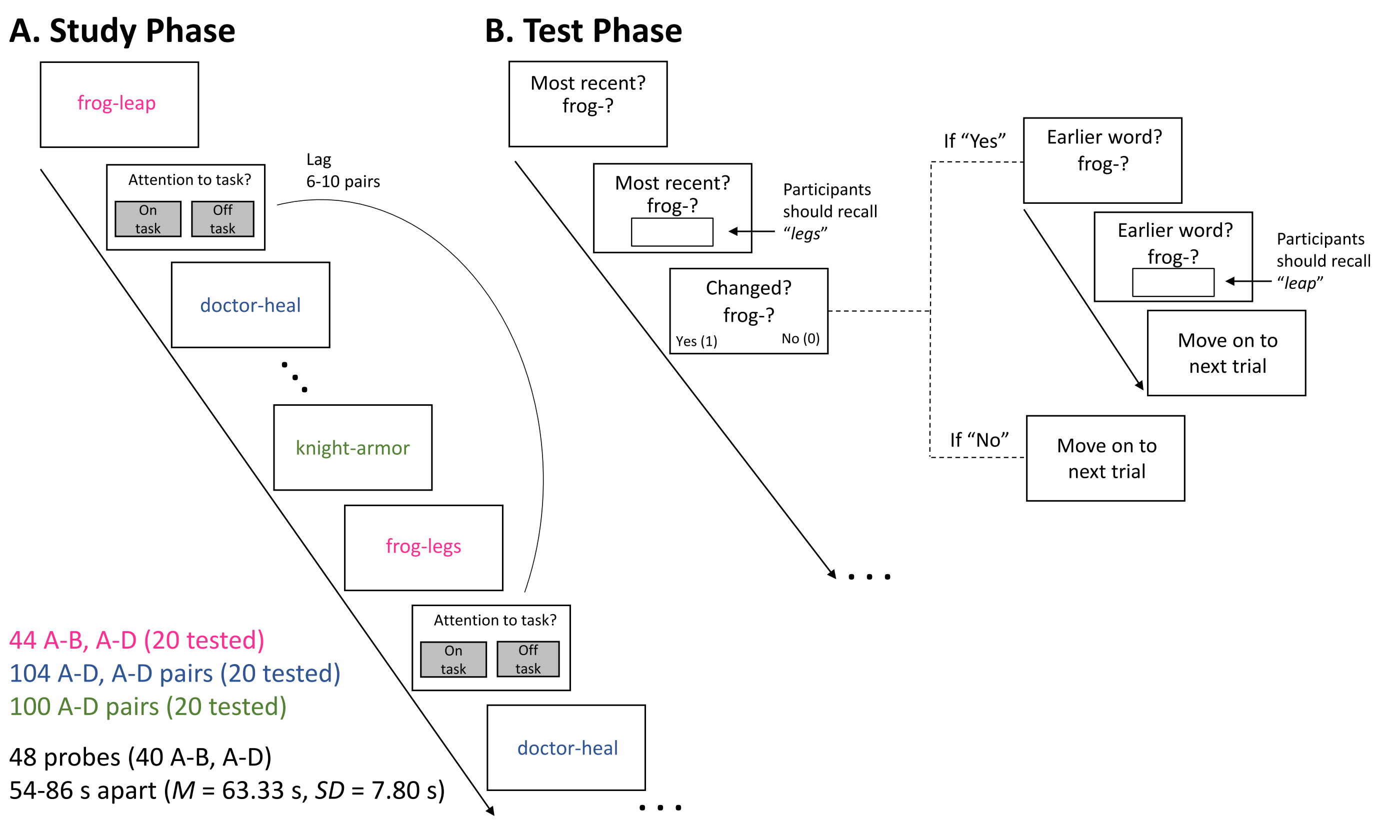

Fig. 1. *Schematic of the Procedure.* During the study phase (panel A), word pairs appeared for 6 s followed by 2 s ISIs, which are not displayed for simplicity. The colored fonts above indicate the three different item types, which comprised pairs with repeated cues and changed responses (A-B, A-D), pairs with repeated cues and responses (A-D, A-D), and pairs that appeared once and did not share elements with other pairs (A-D). In the actual task, word pairs appeared in white against a black background. Thought probes that appeared after 6 to 10 intervening items asked participants to report if they were on or off task during the immediately preceding pair. During the test phase (panel B), cues from the study phase appeared next to question marks. Participants were asked to first recall the recent (or only) response paired with the cue. After entering their response, which then disappeared from the screen, participants were asked whether the response paired with the cue had changed. When participants indicated "Yes," they were asked to recall the response that was originally paired with the cue before moving on to the next trial. When participants indicated "No," they immediately moved on to the next trial.

expected non-exclusive outcomes predicted by both views. If integrative encoding requires that first (B) responses are accessible during A-D study, then recent-response (D) recalls should be positively associated with on-task reports given for both A-B and A-D pairs. If proactive interference effects also require that first (B) responses are accessible, then recent-response (D) recalls should also be positively associated with off-task reports for A-B pairs, indicating reduced accessibility, and on-task reports for A-D pairs. Because both accounts propose that recent (D) response accessibility is required for later remembering recent information as such, albeit in different ways, recent (D) response recalls should be negatively associated with off-task reports for A-D pairs, regardless of probe reports for corresponding A-B pairs. Similarly, because first (B) response accessibility is required for intrusion errors, such intrusions should be positively associated with on-task reports for A-B pairs regardless of probe reports during corresponding A-D pairs.

Importantly, the integrative encoding view predicts parallel patterns of within-subjects associations for "changed" classifications and first-response (B) recalls. These responses both provide downstream assays of relative differences in the extent to which participants noticed changed responses when studying A-D pairs. This assumption is based on findings suggesting that noticing changes often occurs when A-D pairs trigger retrievals of and comparisons with A-B pairs (Wahlheim, 2014; Wahlheim & Jacoby, 2013). The integrative encoding view predicts that the greatest positive association will be between on-task reports to A-B and A-D pairs and these two test responses because noticing changes should be best enabled by successful encoding of earlier and recent events. Additionally, showing that first-response (B) recall for attended A-B pairs is enhanced when A-D pairs are also given on-task reports would provide key evidence that encoded A-D pairs can improve memory for A-B pairs partly via retrieval practice. This contrasts with a strict interference view prediction that better encoding of A-B and A-D pairs will lead to more response competition and therefore impaired first-response (B) recalls.

Our primary hypotheses concerning between-subjects associations between probe reports and test responses are motivated by earlier-reported associations between on-task reports and memory updating (Garlitch & Wahlheim, 2020), studies of individual differences in executive function and interference susceptibility (e.g., Kane & Engle, 2000; Rosen & Engle, 1998), and, more generally, studies of mind wandering and episodic memory (for a review, see Blondé et al., 2022). We expected overall on-task report counts to correlate positively with overall accurate test responses, including those associated with memory updating via integration (i.e., recent-response (D) recalls, first-response (B) recalls, and classifications indicating memory for changes). We also expected that people who sustain their attention well during study would be more likely to show higher recent-response (D) recalls for changed than control pairs (i.e., proactive facilitation), suggesting that they noticed changes and engaged in associative encoding more often. This prediction is critical for testing the integration view, because only that view can account for proactive facilitation. Conversely, we expected that people who sustain their attention more poorly would be more likely to show lower recent-response (D) recalls for changed than control pairs (i.e., proactive interference), suggesting a lesser likelihood of noticing changes and associative encoding. Finally, we expected test responses indicative of successful memory updating to be selectively positively correlated with the frequency of on-task reports to both A-B and A-D pairs because integration requires attending to and encoding both pairs.

Method

The Institutional Review Boards at the University of North Carolina at Greensboro (UNCG; Protocol #IRB-FY24-10) and Towson University (Protocol #2108) approved the research reported here.

Participants

The Psychology Department subject pools at UNCG and Towson University provided access to the participants for the present experiment. The stopping rule was to collect data for one semester. The final sample included 346 participants (254 women, 90 men, 2 undisclosed) aged 18–36, (M = 19.08, SD = 1.76) with 144 from UNCG (ages 18–36) and 202 from Towson University (ages 18–24). Participants received partial course credit as compensation. We tested three extra participants from Towson that were later excluded because either they did not follow instructions (1), the program failed (1), or they dropped out (1).

Design and Materials

The experiment used a within-subjects design with Item Type as the independent variable. The levels of this variable included four types of critical study items that were included on the final cued recall test. The conditions included: pairs that appeared twice during study (A-D, A-D), pairs that appeared once during study (A-D), pairs that appeared twice during study with the same cue and changed responses (A-B, A-D), and another set of changed pairs for which thought probes immediately followed both pairs (A-B, A-D [Probed]). By including both probed and unprobed A-B, A-D items, we were able to determine if probes disrupted encoding (and memory) and, more importantly, examine associations between sustained attention and memory using measures of those constructs from independent item sets.

The critical items appearing in these conditions comprised 80 three-word sets taken from a combination of the stimulus sets in Jacoby (1996) and Nelson et al. (1998). This item set was also used in a related mind wandering study by Garlitch and Wahlheim (2020). We selected the items that had the highest prior cued recall performance for the A-D pair, anticipating that recall levels would be low because of the long study list (described below). Normative recall for these items ranged from .27 to .73 (M = .42, SD = .11). Each three-word set contained a cue (e.g., frog) and two responses (e.g., leap, legs) that altogether comprised the two presentations inherent in the A-B, A-D pairs described above. The two responses had overlapping orthographic features such that each response could complete the same word fragment (e.g., le_), as in Jacoby (1996), but the fragments were not used here. For counterbalancing, the critical sets were divided into four groups of 20 and were rotated through within-subjects conditions across four versions of the experiment. Each group appeared in each condition nearly equally often across participants (each version of the experiment was run 86 or 87 times). One response from each set appeared consistently as the updated response (D) in each version of the experiment.

For the critical items, the average lengths of cues (M = 5.28, SD = 1.63, range = 2–9) and responses (M = 4.74, SD = 1.17, range = 3–8) were matched across groups. The average word frequency, assessed using the Hyperspace Analog to Language method (HAL; Lund & Burgess, 1996), and catalogued by the English Lexicon Project (Balota et al., 2007), was matched across groups for the cues (M = 9.24, SD = 1.48, range = 6–14) and responses (M = 9.35, SD = 1.45, range = 6–14). The forward and backward associative strengths between cues and responses were low on average (forward: M = .06, SD = .09, range = .00-.49; backward: M = .07, SD = .13, range = .00-.69) as indexed by the University of South Florida Free Association norms database (Nelson et al., 1998). The average forward and backward associative strengths between responses within word sets was also low (M = .03, SD = .09, range = .00-.46). In addition to the critical item sets, 168 filler sets served to increase the time between thought probes (described below) and induce mind wandering by lengthening the list. Of these, 101 were taken from Jacoby (1996) and Nelson et al. (1998), while 67 were generated anew. The combination of critical and filler sets produced 396 total study presentations.

In total, there were 104 A-D, A-D pairs (208 presentations), 100 A-D pairs (100 presentations) and 44 A-B, A-D pairs (88 presentations). We included a disproportionally greater number of repeated (A-D, A-D) than changed (A-B, A-D) pairs under the assumption that re-experiencing many repeated events would generally reduce the need to attend during study, thus promoting mind wandering. We also included a larger number of singly presented (A-D) relative to changed pairs so that novelty would not be perfectly confounded with change. We assumed that this would reduce bottom up attentional capture induced by response changes. We also assumed that this would lead participants to notice changes to a greater extent based on retrieval of studied pairs, triggered by shared cues, and comparison with different responses from earlier. In addition to these conceptual rationales for the present list structure, this approach served a practical purpose in that the repeated and single pairs filled out the lags between thought probes.

The final cued recall test included practice and actual test phases in which participants viewed cue words from the study phase, each paired with a question mark. The practice phase included six practice cues derived from filler items. The actual test phase included 80 critical item cues comprising 20 from each of the four within-subject conditions.

Procedure

Fig. 1 displays a schematic of the procedure. Participants were tested in groups of 1–6 with an experimenter present. E-prime 3.0 software (Psychology Software Tools, Inc) controlled stimulus presentation. All stimuli appeared in white Arial size 36 font on a black background.

Before the study phase began, participants were told that they would be asked to study a list of word pairs for a later test. They were also told that they would be asked occasionally to report whether their attention was allocated to the task of learning the word pairs. Participants were told to indicate being "on task" when they were completely focused on learning the pair immediately prior to the probe and to indicate being "off task" when their attention was not completely focused on learning the pair. We chose a two-alternative forced choice thought probe format to simplify the task and streamline the study phase procedure. However, one caveat to this approach is that people sometimes experience thoughts about the task, such as its length or difficulty, that do not indicate task compliance per se (Stawarczyk et al., 2011). By distracting people from an ongoing encoding task, such thoughts may interfere with later memory. In two-alternative forced choice procedures, these thoughts are more often characterized as on than off task (Kane et al., 2021; Robison et al., 2019). Consequently, memory advantages associated with attentive (on task) encoding states inferred from probe reports here are likely to underestimate true differences. We accepted this limitation because finding such associations while facing this self-imposed opposition, if anything, would indicate that any observed effects are robust.

The instructions stated: "In this part of the experiment, you will study word pairs for an upcoming test. Some pairs will repeat, some will appear once, and some will change at a later point in the study phase. For changed word pairs, the left-hand member of a pair will appear later with a different right-hand member (e.g., silly-clown; silly-giggle). Each pair will appear for 6 s. Please learn them all as well as possible for a later test. While you are studying the word pairs, you may notice that your ability to focus your attention on the task waxes and wanes. It is normal for people to experience various levels of attentional engagement over time. We are very interested in understanding how your attention changes throughout this phase. To measure this, we will stop the task every now and then to ask you whether you are giving your full attention to studying the word pairs. When the task stops, you will see a screen that asks you to indicate whether you are ON task or OFF task. If your attention to the word pair just before the probe was completely focused on learning the pair, then indicate that you are ON task. In contrast, if you were thinking about something else and your attention was NOT completely focused on learning the pair, then indicate that you are OFF task. You will report your attentional engagement by clicking an appropriately labeled button on the screen."

During study, each pair appeared for 6 s followed by a 2 s interstimulus interval (ISI). Pairs appeared in a fixed random order with the stipulation that the same item type appeared no more than three times consecutively. The average list position for the A-D pairs in each critical item type was equated to control for serial position effects in subsequent recall. The list included 48 thought probes. Forty probes appeared after the first (20) and second (20) presentations of critical A-B, A-D (Probed) items. In addition, four probes appeared after the first (2) and second (2) presentations of filler A-B, A-D items. Finally, four probes appeared after the first (2) and second (2) presentations of filler A-D, A-D items. Each probe appeared immediately after study trials and before ISIs to improve the accuracy of retrospective self-reports. Probes included a prompt asking participants about their attention to the task. The prompt appeared above "On task" and "Off task" boxes. Participants indicated their task engagement using the mouse to click on a box; there was no deadline for probe responses. The average lag between probes was 7.17 pairs ($SD = 0.97$, range 6–10), which translated into 63.33 s ($SD = 7.80$ s, range = 54–86 s).

After the study phase, participants performed the cued recall test, starting with a practice test. Before practice, they were told that on each test trial they would 1) recall the most recent response from the study list, 2) indicate if they remembered responses changing, and if so, 3) recall the earlier response from the study list. The instructions stated:

"In this part of the experiment, you will be tested on your memory for the word pairs that you just studied. On each trial, the left member of a word pair from the study phase (e.g., silly –?) will appear. Your first task will be to type the word that it was MOST RECENTLY paired with during the study phase. If you cannot think of the word, you may guess or type "pass" to move on. After each response, you will be asked whether the MOST RECENT word on the right from the study phase changed from a word pair that you saw earlier in that phase. The question, "Did the right word change during the study phase?" will appear in the middle of the screen above boxes labeled "Yes (1)" and "No (0)". Sometimes you will remember that the MOST RECENT right word had changed from an earlier pair, such as if the recent pair (silly-giggle) changed from the earlier pair (silly-clown). When this happens, press the "1" key to indicate that you remember the right word changing during the study phase. After you indicate remembering a change, you will be asked to recall the right word that appeared EARLIER with the left word. For example, if you remembered that the word paired with "silly" changed from "clown" (earlier) to "giggle" (most recent), you would be asked to recall "clown" because it was the earlier word. If you cannot remember the earlier word, then you may guess or pass. Type each response on the screen and check your spelling carefully. If you cannot think of the word, you may guess or type "pass" to move on. Other times you will not remember the right word changing during the study phase. When this happens, press the "0" key to indicate that the right word did not change."

On each test trial, a cue-question mark pair appeared above a text box. Participants first typed the response they believed was most recently in that box. When participants pressed "Enter" to submit their response, it disappeared from the screen. Next, a prompt appeared asking if the right word paired with the cue changed during the study list. When they indicated that a pair changed by pressing the "1" key, they were asked to type the response that was paired with the cue earlier in the study list. When participants pressed "Enter" to submit their typed response, the program moved onto the next trial. When participants indicated that a pair did not change by pressing the "0" key, the program moved onto the next trial. Each session was about 1.5 h.

Statistical methods

We examined the effects of interest using linear and logistic mixed-effects models from the *lme4* package (Bates et al., 2015) depending on the type of outcome variable. Linear mixed effects models from the *lmer* function were used to model overall response count data when participants supplied one unique value for each level of item type. Those models included a fixed effect of item type and a random-intercept effect of subject. Logistic mixed effects models from the *glmer* function were used to model conditional recall responses when participants supplied binary values for individual items across combinations of two variables. These models included fixed effects of item type and a conditioning variable as well as random intercept effects of subjects and items. After fitting each model, Wald's χ^2 hypothesis tests were performed using the Anova function from the car package (Fox & Weisberg, 2019). Pairwise comparisons were then performed using the *emmeans* function from the *emmeans* package (Lenth, 2021).

For linear mixed effects models, R^2 effect size estimates for the overall models were calculated using the *r.squaredGLMM* function from the *MuMIn* package (Bartoń, 2024). Those estimates indicated the proportion of variance described by the fixed effect alone (marginal R^2 [R_m^2]) and by the fixed and random effects together (conditional R^2 [R_c^2]). Effect size estimates for pairwise comparisons were computed as Cohen's d (d) using the *eff_size* function from *emmeans*. For generalized linear mixed effects models, effect size estimates for the overall models were also computed as marginal and conditional R^2. The reported estimates represent the empirical proportion of variance described by the models. Effect size estimates for pairwise comparisons were computed as odds ratios (*OR*) provided by *emmeans*. The model specifications are available in the analysis scripts on the OSF: https://osf.io/sdvgb/. Bivariate correlations were computed using the cor.test function in base R. The significance level was $\alpha = .05$.

Results

Thought probe reports

We first characterized the variation in on-task reporting to contextualize the analyses of the associations between self-reported attention during study and cued recall test outcomes. Fig. 2 displays the variation in on-task reporting across all probes, all participants, and combinations of A-B and A-D items. The pattern of task engagement varied across probes in the study phase, as expected (Fig. 2A). Nearly every participant reported being on task for the first thought probe. As the study phase progressed, fewer participants reported being on task. Those rates rose then fluctuated when A-D pairs first appeared in the second half, then decreased until approximately half of the participants reported being on task by the end. The total on-task reports also varied across participants (Fig. 2B) and between A-B and A-D pairs (Fig. 2C). Collectively, the variability in on task reports across trials and participants is consistent with studies of self-reported attention and memory (e.g., Garlitch & Wahlheim, 2020; Wahlheim et al., 2023). More generally, the overall reduction in self-reported attention over time is consistent with the time-on-task vigilance decrements observed in studies of sustained attention (Mackworth, 1950).

Overall cued recall responses

We next characterized the cued recall test response rates across item types (Fig. 3). Doing so also contextualized later analyses comparing self-reported attention and cued recall test outcomes. The top row displays mean counts, and the bottom row displays count variation across participants. Each analysis used a model with a fixed effect of item type including all four levels.

Recent-Response (D) recalls

Fig. 3A and 3E show the counts of recent-response (D) recalls across all item types. The model [$R_m^2 = .14$, $R_c^2 = .76$] indicated a significant effect, $\chi^2(3) = 791.63$, $p < .001$. Recall was significantly higher in the A-D, A-D condition than in the other conditions, smallest $t(1035) = 21.02$, $p < .001$, $d = 1.60$. Recall was also significantly higher in the unprobed A-B, A-D than the A-D control condition, $t(1035) = 3.00$, $p = .01$, $d = 0.23$. No other comparisons were significantly different, largest $t(1035) = 2.41$, $p = .08$, $d = 0.18$. The finding that recall was not lower for A-B, A-D than A-D items suggests that performance in the A-B, A-D conditions reflected a mixture of facilitation and interference that depended on the success of remembering changes (for a review, see Wahlheim et al., 2021). Further, the lack of a significant difference between the A-B, A-D probed and A-B, A-D unprobed conditions provides no evidence to suggest that the provision of probes following A-D pairs disrupted encoding of those pairs.

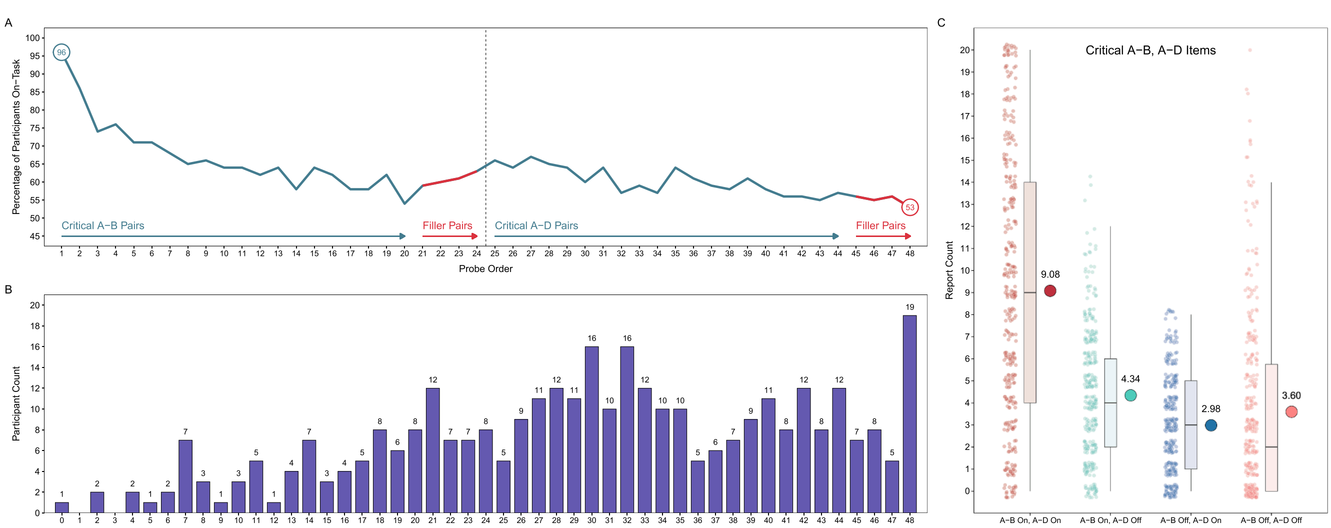

Fig. 2. *On-Task Report Percentages Across Thought Probes, Participants, and Pairs Comprising A-B, A-D Items.* Panel A shows the overall percentages of participants on task at each probe position. Critical A-B and A-D pairs that were later tested appear in blue and filler pairs that were not later tested appear in red. Panel B shows a histogram displaying the inter-individual differences in on-task report counts. Panel C shows the inter-individual differences in combinations of on– and off-task reports for pairs within critical A-B, A-D items. Small points are individual participant counts. Boxplots display medians (center bars), interquartile ranges (upper and lower bars), and 1.5 times interquartile ranges (whiskers). Large points and corresponding numeric text are means. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

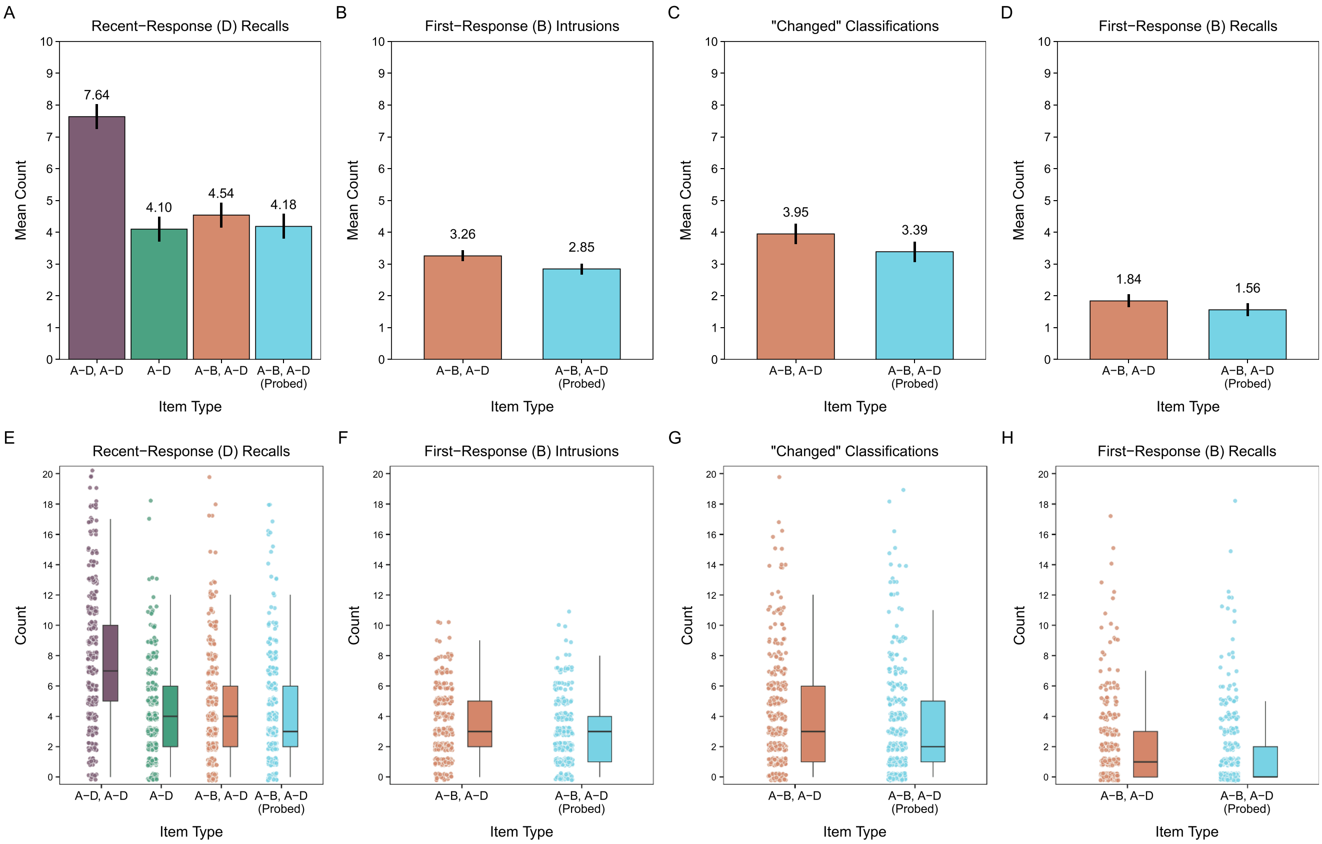

Fig. 3. *Final Cued Recall Test Response Counts.* Panels A-D show the mean counts for all cued recall test responses represented by bar heights and numeric text. Error bars are 95% confidence intervals. Panels E-H show the inter-individual differences in test response counts. Points are individual participant counts. Boxplots display medians (center bars), interquartile ranges (upper and lower bars), and 1.5 times interquartile ranges (whiskers).

First-Response (B) intrusions

Fig. 3B and 3F show the counts of first-responses (B) intrusions in the A-B, A-D conditions. These intrusions are episodic memory errors because participants incorrectly recalled the earlier-studied B responses when asked to recall the more recent D responses. For the A-D, A-D and A-D item types, participants also sometimes reported the responses that would have been B responses had the pairs appeared in the A-B, A-D condition. These intrusions of B responses originated from semantic memory because they never appeared in the experiment. Fig. 3 does not display these rare responses ($M \leq 0.45$). The model [$R_m^2 = .41$, $R_c^2 = .49$] indicated a significant effect, $\chi^2(3) = 1094.60$, $p < .001$. Intrusions were significantly greater in the A-B, A-D conditions than the other conditions, smallest $t(1035) = 21.44$, $p < .001$, $d = 1.63$, showing more episodic than semantic memory errors. Intrusions for A-B, A-D items were significantly lower for probed than unprobed items, $t(1035) = 3.65$, $p < .01$, $d = 0.28$, suggesting that probes may have disrupted encoding of A-B pairs. Finally, intrusions did not differ between the A-D, A-D and A-D conditions, $t(1035) = 0.03$, $p = 1.00$, $d < .01$.

"Changed" classifications

Fig. 3C and 3G show the counts of "changed" classifications (i.e., when participants indicated that responses changed earlier) in the A-B, A-D conditions. Fig. 3 does not display the rare incorrect responses for pairs without changes ($M \leq 1.5$). The model [$R_m^2 = .12$, $R_c^2 = .59$] indicated a significant effect, $\chi^2(3) = 411.02$, $p < .001$, showing significantly higher correct than incorrect classifications, smallest $t(1035) = 12.12$, $p < .001$, $d = 0.92$, significantly higher correct classifications for unprobed than probed A-B, A-D items, $t(1035) = 3.61$, $p < .01$, $d = 0.27$, and no significant difference between A-D, A-D and A-D items, $t(1035) = 0.37$, $p = .98$, $d < .01$. These results showed effective discrimination between cues for changed and unchanged pairs at retrieval and suggested that probes may have disrupted encoding of changes.

First-Response (B) recalls

Fig. 3D and 3H show the counts of correctly recalled B responses for A-B, A-D items that participants reported after classifying items as changed. For the A-D, A-D and A-D item types, such responses were intrusions from semantic memory because the B responses never appeared in the experiment. These rare responses ($M \leq 0.08$) do not appear in Fig. 3. The model [$R_m^2 = .16$, $R_c^2 = .40$] indicated a significant effect, $\chi^2(3) = 360.35$, $p < .001$, showing significantly higher correct recall than intrusions, smallest $t(1035) = 12.13$, $p < .001$, $d = 0.92$, and no other significant effects, largest $t(1035) = 2.30$, $p = .10$, $d = 0.17$. These results showed that first-response (B) recalls were more likely than intrusions of those responses and do not provide evidence that the encoding of those A-B pairs was disrupted by the probes that followed.

A-B, A-D recall conditioned on "Changed" classifications and First-Response (B) recall

We next verified that overall cued recall in the A-B, A-D conditions included a mixture of enhancement and impairment, as in earlier studies (for a review, see Wahlheim et al., 2021). Here, we showed interdependence between recent (D) and first (B) response recall for A-B, A-D items that was consistent with our original study of sustained attention and episodic memory updating (Garlitch & Wahlheim, 2020). Response interdependence was assessed by conditioning recent-response (D) recalls and first-response (B) intrusions on combinations of "changed" classifications and first-response (B) recalls (Fig. 4). We used separate logistic mixed effects models for each response. Each model included fixed effects of Item Type and Classification (classification/first-response [B] recall combinations). Item Type included probed and unprobed A-B, A-D conditions. Classification included "changed" classifications with and without first-response recalls and "not changed" classifications. First-response (B) intrusions and first-response (B) recalls following "changed" classifications both referred to B responses. This cell indicates the extent to which participants failed to comply with the test instructions by providing the same response (B) twice consecutively. Finally, we focused only on the effects involving Classification and do not elaborate on Item Type effects redundant with those described above.

Recent-Response (D) recalls

Fig. 4 (left) displays conditional recent-response (D) recalls. The model [$R_m^2 = .08$, $R_c^2 = .24$] indicated a significant effect of Classification, $\chi^2(2) = 887.70$, $p < .001$, no significant effect of Item Type, $\chi^2(1) = 3.38$, $p = .07$, and no significant interaction, $\chi^2(2) = 0.51$, $p = .78$. As shown before, the probability of recent-response (D) recalls was significantly higher for items classified as changed with first-response (B) recalls than items classified as changed without first-response (B) recalls, z ratio = 22.26, $p < .001$, $OR = 0.07$, and items not classified as changed, z ratio = 29.67, $p < .001$, $OR = 15.91$. First-response (B) recalls did not differ between the latter cells, z ratio = 1.83, $p = .16$, $OR = 1.17$. The enhancement in recent-response (D) recalls associated with first-response (B) recalls suggests that memory for a subset of items benefitted from associative encoding that supported later recollection. In contrast, the impairment in recent-response (D) recalls for the other items suggests that proactive interference from A-B pairs occurred when recollection of encoded changes failed.

First-Response (B) intrusions

Fig. 4 (right) displays conditional first-response (B) intrusions. The model [$R_m^2 = .08$, $R_c^2 = .18$] indicated significant effects of Classification, $\chi^2(2) = 286.76$, $p < .001$, and Item Type, $\chi^2(1) = 14.93$, $p < .001$, and no significant interaction, $\chi^2(2) = 1.07$, $p = .59$. As shown before,

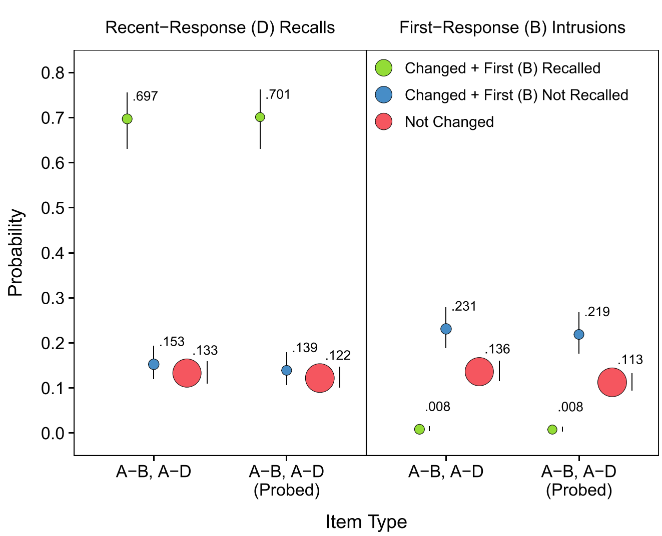

Fig. 4. *Probabilities of Recent-Response Recalls and First-Response Intrusions Conditioned on "Changed" Classifications and First-Response Recalls for A-B, A-D Items.* The values indicated by point heights and numeric text are probabilities estimated from logistic mixed effects models. The point areas indicate the relative differences in observations per cell. Error bars are 95% confidence intervals; they are displayed to the right of points when the intervals are smaller than the point diameters.

the probability of first-response (B) intrusions was significantly higher for items classified as changed without first-response (B) recalls than items not classified as changed, z ratio = 9.34, $p < .001$, $OR = 2.05$. The latter was significantly higher than the probability of first-response (B) intrusions when items were classified as changed with first-response (B) recalls, z ratio = 13.52, $p < .001$, $OR = 0.06$. The extremely low probability of intrusions when B responses were recalled indicated that participants followed the task instructions by rarely reporting the B response twice consecutively. Moreover, the higher intrusion rates for items classified as "changed" suggested that changes were noticed and later remembered for more accessible B responses, which sometimes came to mind without the context needed to withhold reporting.

A-B, A-D recall conditioned on probe report combinations

Our previous study of sustained attention and episodic memory updating showed that self-reported attention while studying A-D pairs was associated with better memory for D responses, that they changed, and the B responses from which they changed (Garlitch & Wahlheim, 2020). However, that study did not assess the role of attention to A-B pairs in those associations. The inclusion of thought probes after corresponding A-B and A-D items allowed us to assess that role here. Within-subjects associations between probe reports and cued recall responses are reported in what follows. Those associations were assessed using separate logistic mixed effects models with a fixed effect of Probe Report including the four report combinations for each outcome variable. A reviewer pointed out that several participants had low variability in probe reports (see Fig. 2C) and that this might reduce the precision of the probability estimates for the complete sample. This concern was addressed by modeling data from the complete sample ($n = 346$; Fig. 5A) and a restricted sample including only participants with at least one observation for each probe report combination ($n = 210$; Fig. 5B). This inclusion criterion was chosen a priori based on Garlitch and Wahlheim to avoid being influenced by the current patterns of results.

Recent-Response (D) recalls

Fig. 5A and 5B (left) show the probabilities of recent-response (D) recalls. The model for the complete sample [$R_m^2 = .02$, $R_c^2 = .23$] indicated a significant effect, $\chi^2(3) = 103.35$, $p < .001$. The probabilities were significantly higher when participants reported being on task than off task while studying A-D pairs, regardless of A-B probe reports, smallest z ratio = 6.85, $p < .001$, $OR = 2.23$. No other differences were significant, largest z ratio = 0.64, $p = .92$, $OR = 0.92$. The model for the restricted sample [$R_m^2 = .02$, $R_c^2 = .19$] also indicated a significant effect, $\chi^2(3) = 63.03$, $p < .001$. As for the complete sample, the probabilities in the restricted sample were significantly higher when participants reported being on task than off task while studying A-D pairs, regardless of A-B probe reports, smallest z ratio = 5.30, $p < .001$, $OR = 0.49$. No other differences were significant, largest z ratio = 0.53, $p = .95$, $OR = 1.07$. These results suggest that attention to A-D pairs promoted recent-response (D) recalls by promoting associative encoding when participants had earlier attended to A-B pairs or by making D responses more accessible than B responses that were less well attended.

First-response (B) intrusions

Fig. 5A and 5B (left-middle) show the probabilities of first-response (B) intrusions. The model for the complete sample [$R_m^2 = .01$, $R_c^2 = .09$] indicated a significant effect, $\chi^2(3) = 26.99$, $p < .001$. The probabilities were significantly higher when participants reported being on task than off task while studying A-B pairs, regardless of A-D reports, smallest z ratio = 3.17, $p < .01$, $OR = 0.69$. No other differences were significant, largest z ratio = 0.96, $p = .77$, $OR = 1.09$. The model for the restricted sample [$R_m^2 = .01$, $R_c^2 = .10$] also indicated a significant effect, $\chi^2(3) = 29.74$, $p < .001$, showing significantly higher probabilities when

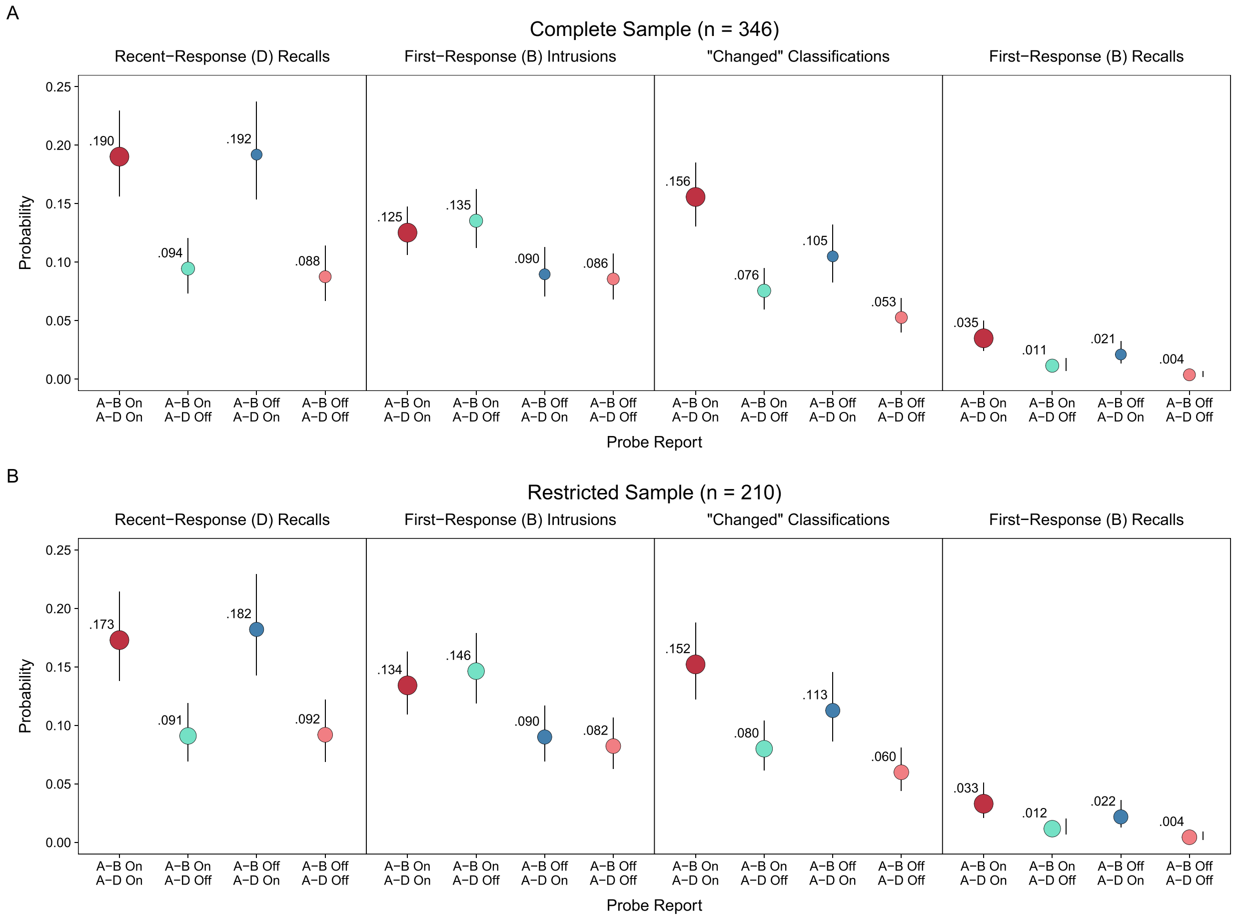

Fig. 5. *Probabilities of Final Cued Recall Test Responses Conditioned on Probe Reports for Probed A-B, A-D Items.* Probe reports on the x-axes indicate the four possible combinations of responses to probes after A-B and A-D pairs. Panel A shows values from the complete sample. Panel B shows values from a restricted sample including only the participants who provided at least one probe report of each type. The values are probabilities estimated from logistic mixed effects models. Values appear as point heights and in numeric text. The point areas indicate the relative differences in observations per cell. Error bars are 95% confidence intervals and are displayed to the right of points with diameters that are larger than the intervals.

participants reported being on task than off task while studying A-B pairs, regardless of A-D reports, smallest z ratio = 3.20, $p < .01$, OR = 0.64. No other differences were significant, largest z ratio = 0.89, p = .81, OR = 1.11. These results suggest that attention to A-B pairs promoted the accessibility of B responses, which was sometimes misattributed as recency, thus leading to intrusions.

"Changed" classifications

Fig. 5A and 5B (right-middle) show the probabilities of "changed" classifications. The model for the complete sample [R_m^2 = .02, R_c^2 = .22] indicated a significant effect, $\chi^2(3) = 103.85$, $p < .001$. The probabilities were significantly different across all probe reports and decreased in the following order: A-B on, A-D on > A-B off, A-D on, z ratio = 4.08, $p < .001$, OR = 0.64; A-B off, A-D on > A-B on, A-D off, z ratio = 2.76, p = .03, OR = 1.43; and A-B on, A-D off > A-B off, A-D off, z ratio = 2.69, p = .04, OR = 0.68. The model for the restricted sample [R_m^2 = .02, R_c^2 = .20] also indicated a significant effect, $\chi^2(3) = 60.15$, $p < .001$, showing that the probabilities were significantly different across all probe reports in the same order with one exception. There was no significant difference between A-B on, A-D off and A-B off, A-D off reports, z ratio = 1.95, p = .21, OR = 0.73. The remaining probabilities decreased as follows: A-B on, A-D on > A-B off, A-D on, z ratio = 2.64, p = .04, OR = 0.71; and A-B off, A-D on > A-B on, A-D off, z ratio = 2.59, $p < .05$, OR = 1.46. These patterns suggest that attention to both A-B and A-D pairs best promoted the noticing and later remembering of changes.

First-response (B) recalls

Fig. 5A and 5B (right) show the probabilities of first-response (B) recalls. The model for the complete sample [R_m^2 = .04, R_c^2 = .25] indicated a significant effect, $\chi^2(3) = 85.46$, $p < .001$. The probabilities were significantly different across all probe reports and decreased in the following order: A-B on, A-D on > A-B off, A-D on, z ratio = 3.14, $p < .01$, OR = 0.59; A-B off, A-D on > A-B on, A-D off, z ratio = 2.90, p = .02, OR = 1.85; and A-B on, A-D off > A-B off, A-D off, z ratio = 3.68, $p < .01$, OR = 0.32. The model for the restricted sample [R_m^2 = .01, R_c^2 = .10] also indicated a significant effect, $\chi^2(3) = 55.18$, $p < .001$, showing the same pattern as the complete sample with one exception. There was no significant difference between A-B on, A-D on and A-B off, A-D on reports, z ratio = 2.14, p = .14, OR = 0.65, but recall for those reports was significantly greater than for the other reports, which decreased in the same order as for the complete sample: A-B off, A-D on > A-B on, A-D off, z ratio = 2.58, $p < .05$, OR = 1.88; and A-B on, A-D off > A-B off, A-D off, z ratio = 2.91, p = .02, OR = 0.37.

As for "changed" classifications, these patterns also suggest that attention to both A-B and A-D pairs best promoted the noticing and later remembering of changes. Importantly, these results show that attending to A-B and A-D pairs promoted the best recall of B responses, which was strongly positively associated with recent-response (D) recalls (see Fig. 4). Collectively, these findings are consistent with the view that attention to both earlier and more recent events is necessary to enable associative encoding of changed pairs and recollection-based retrieval of such changes in the service of updating episodic memory and mitigating proactive interference.

Individual differences in self-reported attention and cued recall test responses

The prior analyses showed that attentive encoding to study items within participants was associated with enhanced subsequent memory. Taken with the variability in the extent to which participants were able to sustain their attention during study (see Fig. 2), the within-subject associations suggest that participants who sustain their attention more effectively should also show associated global enhancements in subsequent memory. Such associations would have theoretical implications in suggesting that participants with better sustained attention should better resist interference, possibly by more frequently associating and recollecting earlier and more recent events. In the following analyses, we characterized the between-subject associations between probe reports and subsequent memory. Our first goal was to verify that attentive encoding is associated with better subsequent memory, regardless of the potential for proactive interference. Our second goal was to determine if variations in self-reported attention associate with memory updating similar to prior findings showing that constructs associated with attention control, which may be related to sustained attention, are associated with interference resistance (Kane & Engle, 2000; Rosen & Engle, 1998). We predicted that on-task reports indicating sustained attention would be correlated with better subsequent memory.

Correlations Between Total On-Task Reports and Test Responses

To verify that people who better sustained their attention during study showed better subsequent memory, we computed correlations between the total count of on-task reports during study (summed across all 48 probes) and recent-response (D) recalls for the unprobed item types (Fig. 6A). We also computed correlations between on-task counts and the other possible test responses for A-B, A-D items (Fig. 6B). Based on findings from Garlitch and Wahlheim (2020) and the mind wandering and memory literature more generally (Blondé et al., 2022), we expected on-task counts to correlate positively with every response except first-response (B) intrusions. All scatter plots with recent recent-response (D) recalls as the outcome measure indicated significantly positive correlations, *ps* $< .001$. The scatter plots with “changed” classifications and first-response (B) recalls as the outcome measures

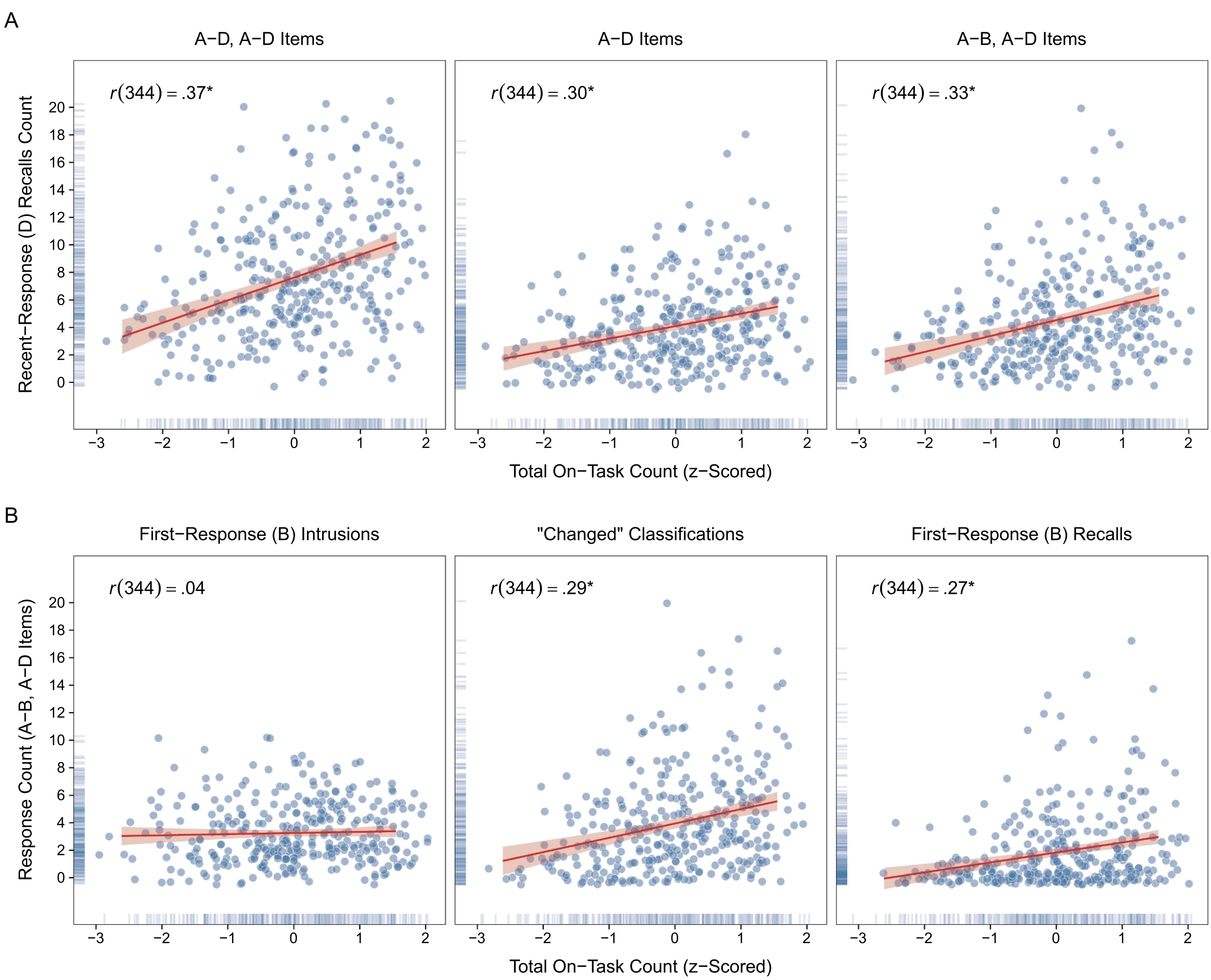

Fig. 6. *Between-Subjects Correlations for Total On-Task Reports and Final Cued Recall Test Responses.* Scatter plots depicting associations between z-scored counts of total on-task reports to all probed A-B, A-D items and raw test response counts for unprobed item types. Panel A shows the associations with recent-response (D) recalls as the outcome measure for all unprobed item types. Panel B shows the associations with first-response (B) intrusions (left pane), “changed” classifications (middle pane), and first-response (B) recalls (right pane) for unprobed A-B, A-D items as the outcome measures. The shaded regions around the regression lines are 95 % confidence intervals. The rugs indicate frequency distributions for each measure. * $p < .001$.

also showed significantly positive correlations, *ps* < .001. Conversely, the scatter plot with first-response (B) intrusions as the outcome measure showed no significant correlation, $p = .49$. These results replicate prior findings suggesting that people who better sustain their attention during study show better subsequent episodic memory, including when response competition is present.

Individual differences in sustained attention and proactive effects of memory

To further examine the association between sustained attention and memory accuracy when response competition was present, we further examined the relationship between on-task reports and subsequent recent-response (D) recalls for A-B, A-D items. We predicted that participants who better sustained their attention during study would be more likely to show proactive facilitation. Importantly, neither a strict interference nor neural differentiation view cannot account for proactive facilitation effects; but a view positing a role for integrative encoding can do so. To test this hypothesis, participants were assigned to quartiles based on their on-task report counts, and recent-response (D) recalls were compared for the A-D (control) and A-B, A-D (changed) items.

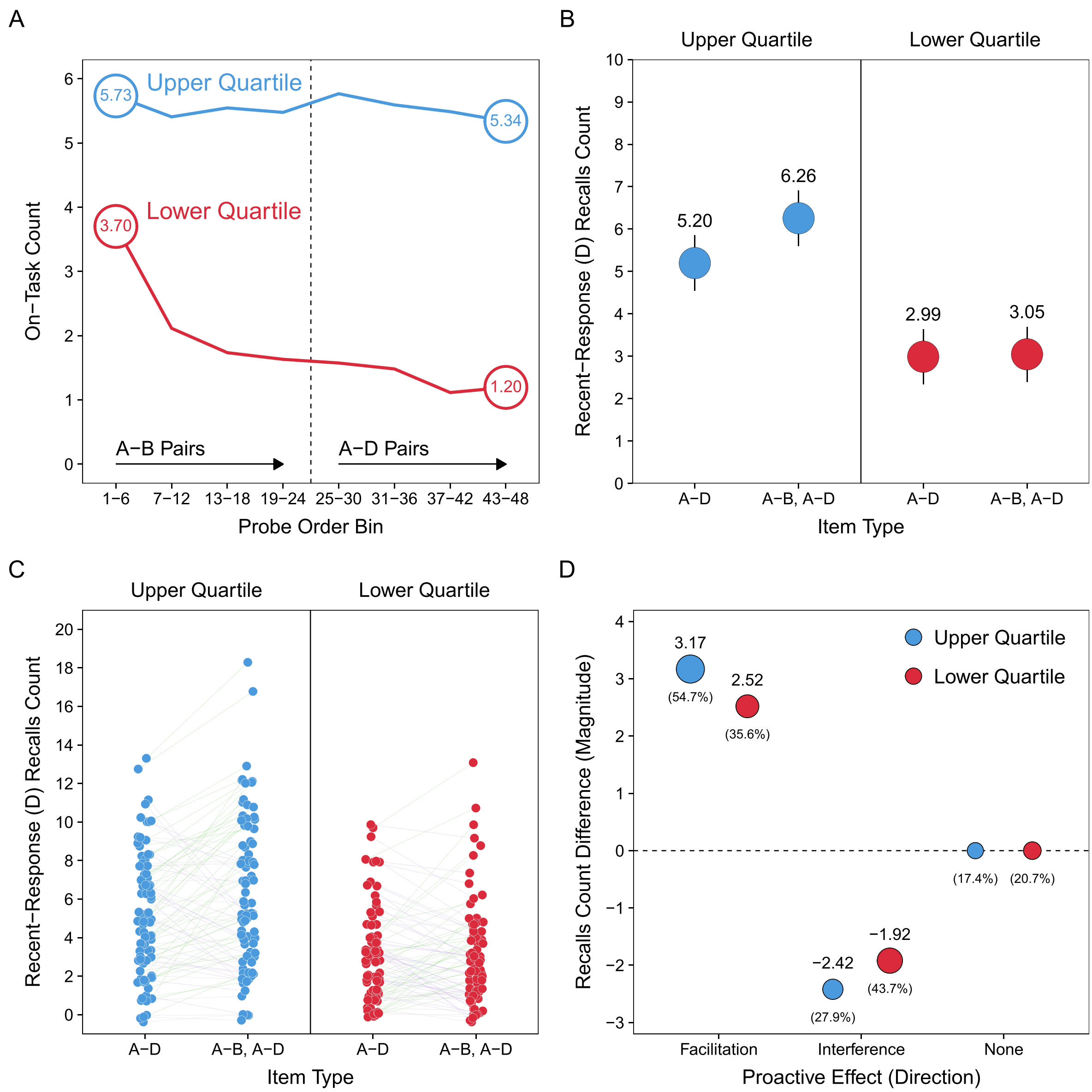

Fig. 7. *Extreme-Groups Between-Subjects Associations between Total On-Task Reports and Proactive Effects of Memory on Recent-Response (D) Recalls.* Panel A shows the mean on-task report counts in six-probe bins across the study phase for participants in the upper and lower quartile of total on-task reports to all probed A-B pairs (left pane) and A-D pairs (right pane). The text values indicate the means in the first and last bins. Panel B shows the mean recent-response (D) recalls for unprobed A-D (control) and A-B, A-D (changed) item types in each on-task quartile. The text values indicate the means, and the error bars are 95 % confidence intervals. Panel C shows the recent-response (D) recalls counts for each participant (points) and item type in each on-task quartile. The slopes of the connecting lines indicate which participants showed proactive facilitation (positive, green lines), proactive interference (negative, purple lines) or no proactive effect (no slopes, gray lines). Jitter applied to the points after computing difference scores led to uneven slopes for the true zero-difference slopes that are colored in gray. Panel D shows descriptive statistics that summarize the recent-response (D) recalls slope differences between on-task quartile groups shown in Panel C. The signs of the points indicate the direction of the proactive effects (positive = facilitation, negative = interference). The point heights and text above the points indicate the mean magnitudes of difference scores. The points sizes and percentages in parentheses below the points indicate the differences in the percentages of participants in each cell. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

On-task differences across study trials were characterized for the upper (n = 86) and lower (n = 87) quartiles (Fig. 7A). Mean counts were computed across every six probes and compared using a model with Quartile (Upper vs. Lower) and Bin (1–8) as fixed effects. The model [$R_m^2 = .77$, $R_c^2 = .81$] indicated significant effects of Quartile, $\chi^2(1) = 1927.25$, $p < .001$, and Bin, $\chi^2(7) = 266.28$, $p < .001$, and a significant interaction, $\chi^2(7) = 185.84$, $p < .001$. The upper quartile showed highly sustained attention across trials with only slightly lower on-task reports in the last than first bin. The lower quartile showed poorly sustained attention, with lower initial attention than shown by the upper quartile, followed by a precipitous decrease that ended near the bottom of the scale.

These group differences in attention during study were associated with differences in memory updating. Proactive effects of memory on recent-response (D) recalls (Fig. 7B) were compared with a model including Quartile and Item Type (A-D vs. A-B, A-D) as fixed effects. Proactive facilitation is indicated by higher recall for A-B, A-D than A-D items, whereas proactive interference is indicated by lower recall for A-B, A-D than A-D items. The model indicated [$R_m^2 = .17$, $R_c^2 = .71$] a significant effect of Quartile, $\chi^2(1) = 40.76$, $p < .001$, showing higher recall for the upper than lower quartile. The model also indicated a significant effect of Item Type, $\chi^2(1) = 7.93$, $p < .01$, and a significant interaction, $\chi^2(1) = 6.44$, $p = .01$. The upper quartile showed proactive facilitation as performance was significantly higher for A-B, A-D than A-D items, $t(171) = 3.79$, $p < .001$. In contrast, the lower quartile showed no overall proactive effect of memory as performance did not differ between item types, $t(171) = 0.21$, $p = .84$.

To characterize the individual differences in recent-response (D)

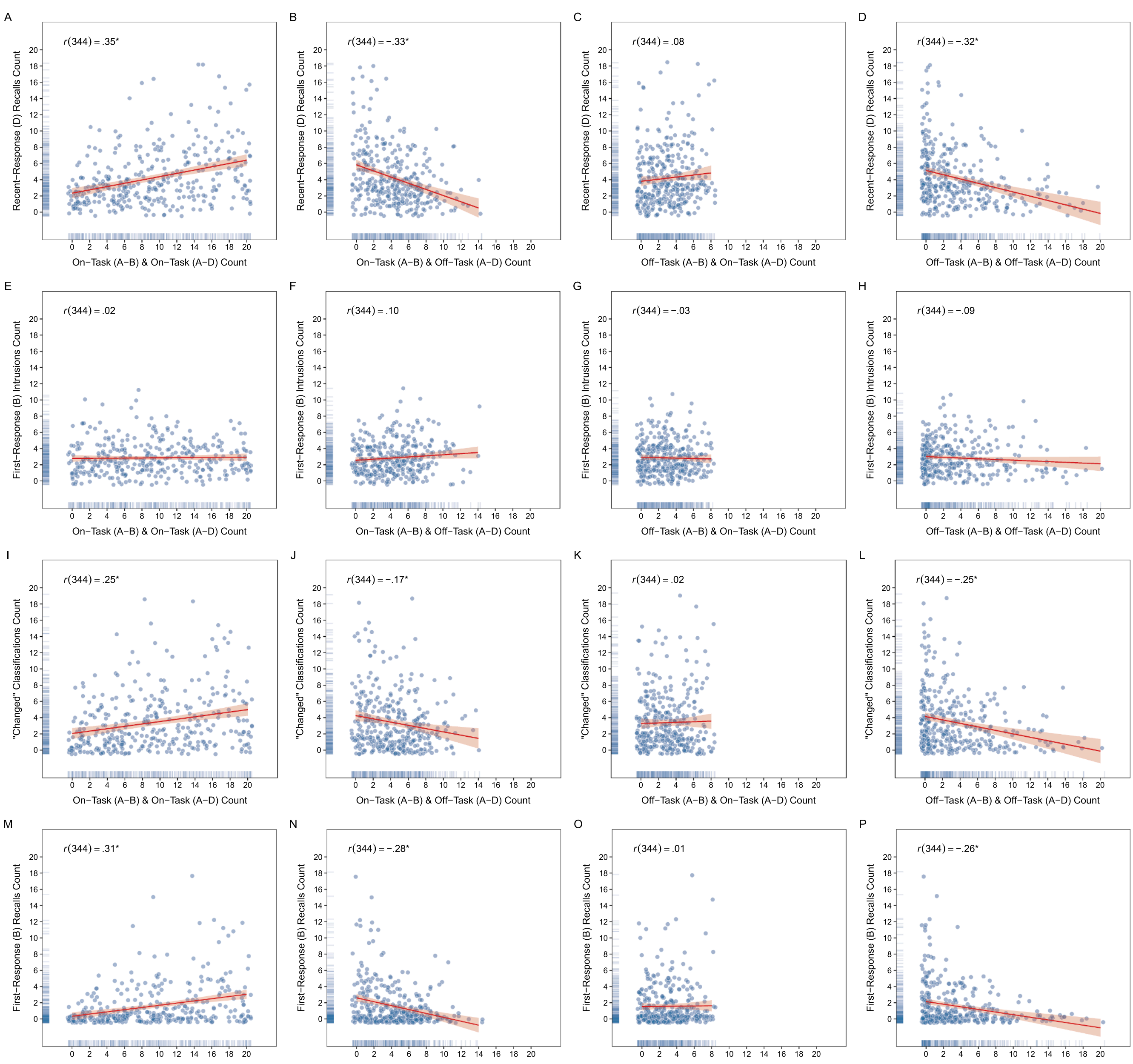

Fig. 8. *Between-Subjects Correlations for Combinations of Task Reports for Probed A-B, A-D Items and Final Cued Recall Test Responses.* Scatter plots depicting associations between counts of on– and off-task reports to pairs in probed A-B, A-D items and test response counts for those items as the outcome measures. Panels A-D show the associations with recent-response (D) recalls; Panels E-H show the associations with first-response (B) intrusions; Panels I-J show the associations with "changed" classifications; and Panels M−P show the associations with first-response (B) recalls. The shaded regions around the regression lines are 95 % confidence intervals. The rugs indicate frequency distributions for each measure. * $p < .001$.

recalls that led to these group differences, Fig. 7C and 7D provide descriptive statistics summarizing the directions of slopes between item types as well as their frequencies and magnitudes across participants. These summaries show that the difference in overall recall between groups showing facilitation in the upper quartile and no effect for the lower quartile reflected differences in both the frequencies and magnitudes of participant-level differences. Specifically, proactive facilitation (positive slopes) was observed for a higher percentage of participants in the upper (54.7 %) than lower (35.6 %) quartile, proactive interference (negative slopes) was observed for a lower percentage of participants in the upper (27.9 %) than lower (43.7 %) quartile, and no proactive effect (zero slopes) was observed for a lower percentage of participants in the upper (17.4 %) than lower (20.7 %) quartile. The magnitudes of proactive facilitation and interference were both greater for the upper than lower quartile. Collectively, these results are consistent with the view that better sustained attention during study can counteract response competition and promote associative encoding that leads to proactive facilitation in overall recent-response recall.

Correlations between probe reports for A-B and A-D pairs, and test responses

To examine the extent to which individual differences in attention were associated with recall of responses from A-B, A-D items and classifications indicating memory for changes, we correlated counts of on-task report combinations of A-B and A-D pairs with each cued recall test response (Fig. 8). Similar to the within-subjects associations above, we expected that participants who more often report being on task for both A-B and A-D pairs should show higher response rates indicative of successful memory updating, namely recent-response (D) recalls, "changed" classifications, and first-response (B) recalls. Conversely, such positive associations should not be observed for off-task probe reports, because those reports indicate more inattentive states during study that would preclude noticing and remembering changes.

Recent-response (D) recalls. Fig. 8 (A-D) displays scatter plots with recent-response (D) recalls as the outcome measure. Panel A shows that probe reports were significantly positively correlated with recent-response (D) recalls when participants reported being on task for both A-B and A-D pairs, $p < .001$. In contrast, probe reports were significantly negatively correlated with recent-response (D) recalls when participants were on task for A-B pairs and off task for A-D pairs (panel B) or were off task for both pairs (panel D), $ps < .001$. Finally, there was no significant correlation between probe reports and recent-response (D) recalls when participants were off task for A-B pairs and on task for A-D pairs (panel C), $p = .12$. Collectively, these results suggest that positive correlations between on-task reports to A-D pairs and recent-response (D) recalls in Garlitch and Wahlheim (2020) were carried by instances of attentive study to A-B and A-D pairs.

First-response (B) intrusions. Fig. 8 (E-H) displays scatter plots with first-response (B) intrusions as the outcome measure. No probe reports were significantly correlated with intrusions, $ps \geq .06$. This lack of correlations may reflect tradeoffs in the consequences of B response accessibility. Intrusions require a sufficient level of encoding to later be emitted, but effective encoding that preserves temporal information also enables rejections. These patterns could also reflect the lower reliability of the intrusion measure ($r = .41$, see Table 1).

"Changed" classifications and first-response (B) recalls. Fig. 8 displays scatter plots with "changed" classifications (I-L) and first-response (B) recalls (M−P) as the outcome measures. Both outcomes appear together because participants often use memory for first responses as a basis for classifying items as changed; consequently, the patterns were the same. Both outcomes were significantly positively correlated with on-task reports for A-B and A-D pairs (panels I and M) and significantly negatively correlated with on-task reports for only A-B pairs (panels J and N) as well as off-task reports for A-B and A-D pairs (panels L and P), $ps \leq .001$. Both outcomes were not significantly correlated with on-task reports for only A-D pairs (panels K and O), $ps \geq .67$. These patterns are consistent with the idea that associative encoding that promotes memory for changes is best when both pairs are studied attentively.

Discussion

The present experiment examined the role of attention while studying changes across paired associates in subsequent episodic memory updating. It established within- and between-subject associations between self-reported task engagement during study, which varied widely across participants, and subsequent memory for recent (D) responses and whether they changed from earlier (B) responses. Recall of recent (D) responses for changed (A-B, A-D) pairs was comparable to or higher than recall of those responses for control (A-D) pairs, suggesting that some A-B and A-D pairs were associatively encoded during study. More evidence for such encoding was shown by recall of recent (D) responses being highest when changes were remembered and the first (B) responses that changed were recalled. Within participants, remembering changes and recalling B responses that changed during study was more strongly associated with on-task reports for both A-B and A-D pairs than any other combination of probe reports. Similarly, between participants, positive correlations with these memory outcomes were only observed for on-task reports for both A-B and A-D pairs. Finally, individual

Table 1
Descriptive Statistics and Reliability Estimates for Probe Report and Final Cued Recall Test Measures.

Items	Measure	*M*	*SD*	Skew	Kurtosis	Reliability
Probed Critical and Filler A-B, A-D Items	Total On-Task Reports	30.12	11.53	−0.35	2.38	.95
Unprobed Critical Items	Recent-Response (D) Recalls (A-D, A-D)	7.64	4.46	0.62	2.91	.82
	Recent-Response (D) Recalls (A-D)	4.10	3.06	1.07	4.55	.68
	Recent-Response (D) Recalls (A-B, A-D)	4.54	3.54	1.20	4.66	.77
	First-Response (B) Intrusions (A-B, A-D)	3.26	2.23	0.66	2.84	.49
	"Changed" Classifications (A-B, A-D)	3.95	3.62	1.30	4.91	.79
	First-Response (B) Recalls (A-B, A-D)	1.84	2.73	2.35	9.70	.81
Probed Critical A-B, A-D Items	On-Task (A-B) & On-Task (A-D)	9.08	5.99	0.25	1.95	.92
	On-Task (A-B) & Off-Task (A-D)	4.34	3.01	0.50	2.82	.72
	Off-Task (A-B) & On-Task (A-D)	2.98	2.23	0.35	2.18	.57
	Off-Task (A-B) & Off-Task (A-D)	3.60	4.12	1.44	4.75	.88
	Recent-Response (D) Recalls	4.18	3.45	1.41	5.37	.76
	First-Response (B) Intrusions	2.85	2.04	0.92	3.98	.41
	"Changed" Classifications	3.39	3.52	1.56	5.69	.82
	First-Response (B) Recalls	1.56	2.61	2.65	11.89	.83

Note. Reliability was calculated using the "splithalf" package in R with the odd/even method, 5000 permutations, and with the Spearman-Brown correction applied (Spearman, 1904). The measures using probed critical and filler A-B, A-D items and unprobed critical items were included in the correlations displayed in Fig. 6. The measures using probed critical A-B, A-D items were included in the correlations displayed in Fig. 8.

differences in overall sustained attention during study predicted patterns of memory performance: More participants showed proactive facilitation in the form of higher D response recall for A-B, A-D than A-D pairs in the upper than lower quartile of on-task reports. Conversely, more participants showed proactive interference in the form of lower D response recall for A-B, A-D than A-D pairs in the lower than upper quartile of on-task reports. These results highlight the importance of attending to, and the cost of inattention to, A-B and A-D pairs for episodic memory updating. In what follows, we discuss the theoretical implications of these and other current findings as well as their relationship to the literature on attention and memory.

As described in the Introduction, the integration and interference views make opposite predictions about the subsequent memory effects of A-D pairs triggering retrievals of earlier-studied A-B pairs. Specifically, the integration view proposes that such retrievals engender the co-activation of responses, which provides the opportunity for associative encoding and subsequent enhancement in the recollection of recent responses. Conversely, the interference view proposes that retrieving A-B pairs when studying A-D pairs leads B responses to become associated with both list contexts, thus making them more competitive with D responses at test. A more comprehensive view, the MFC framework, includes roles for both integration and interference mechanisms in episodic memory updating (Wahlheim & Jacoby, 2013). It proposes that study-phase retrievals of A-B pairs can improve memory for D responses to the extent that such retrievals engender integrative encoding and subsequent recollection-based retrieval of both responses and their temporal relationship. However, when co-activation occurs but subsequent recollection fails, the association of A-B pairs with both lists should lead to proactive interference effects in the form of lower recall of updated D responses. The assumption that integration and interference both contribute to overall performance in A-B, A-D protocols leads to predictions about the role of attention during study in subsequent recall dynamics.

If integration promotes updating, then attending to both A-B and A-D pairs should lead the pairs to be encoded sufficiently for A-D pairs to trigger A-B retrievals and their mnemonic consequences (i.e., memory for item-specific and associative information). Accordingly, on-task reports during A-B and A-D study should be positively associated with memory for D responses, the fact that they changed, and memory for corresponding B responses. The present results showed these associations within- and between-subjects. Moreover, if disambiguating the list contexts associated with A-B and A-D pairs also contributes to updating by reducing proactive interference, then being off-task while studying A-B pairs and on-task while studying A-D pairs should reduce interference from B responses. Within-subject associations support this prediction, as probe reports comprising off-task (A-B) and on-task (A-D) were positively associated with recent-response (D) recalls and negatively associated with first-response (B) intrusions. The corresponding between-subjects correlations were not significant, which may have reflected the lower reliability of that probe report combination ($r = .57$) relative to the other probe reports (rs $\geq .72$). Finally, consistent with the MFC framework prediction that attention to A-D items should promote retrieval of earlier-attended A-B items, associative encoding, and recollection of changes—the probe reports comprising off-task to A-B pairs and on-task to A-D pairs showed weaker positive within-subject associations with remembering changes and B response recalls than on-task reports to both pairs. Together, these findings suggest that the encoding variability attendant to the attentional fluctuations across trials determines the extent to which memory for recent responses is supported by integrated or disambiguated temporal contextual associations.

The present study builds directly upon an earlier study showing associations between self-reported attention and episodic memory updating in an A-B, A-D protocol (Garlitch & Wahlheim, 2020). That study showed that on-task reports to A-D pairs were associated with subsequent memory for first (B) and recent (D) responses and the fact that they changed. However, that study did not systematically assess attention to A-B pairs. The present within-subjects associations showed that on-task reports to A-B and A-D as well as to only A-D pairs were predictive of higher recent-response (D) recalls. These findings suggest that the positive within-subjects associations involving on-task reports to A-D pairs shown before reflected a mix of trials for which some A-B pairs were attended, whereas others were not. Also, the present between-subjects correlations showed that individual differences in recent-response (D) recalls were only positively associated with on-task reports to both A-B and A-D pairs. These results suggest that the positive between-subjects correlations shown before were carried by instances when participants were on task while studying A-B pairs. Such instances may have occurred more often in Garlitch and Wahlheim (2020) because participants studied A-B pairs three times (compared to once here), and thus had more chances to attend to those pairs.

The findings from these two memory updating studies are relevant to perspectives on the consequences of inattention for memory and comprehension. Inattention that occurs during mind wandering is believed to undermine semantic encoding (e.g., Maillet et al., 2017; Thomson et al., 2014), and recollection-based retrieval (e.g., Maillet & Rajah, 2014; Miller & Unsworth, 2021; Smallwood et al., 2007), similar to negative mnemonic consequences of dividing attention during study (e.g., Castel & Craik, 2003; Jacoby, 1991; Mulligan, 1998). Regardless of whether memory for recent events benefits from integration or the inaccessibility of otherwise competing information, updating requires the formation of item-context associations that can be later recollected. The present findings suggest that divided attention states, operationalized as off-task reports, were associated with memory impairment across item and relational information (i.e., changed responses and memory for whether they changed), that may partly have reflected impaired detection of changed features during study. Converging evidence that mind wandering is associated with poorer encoding of item changes comes from mnemonic discrimination studies showing that impaired identification of lure objects as being similar but not identical to studied objects partly reflects impaired recollection of studied objects (Wahlheim et al., 2023, 2024). Moreover, the inference that mind wandering during either or both A-B and A-D pairs prevents people from noticing relationships is consistent with a study showing that situation model updating, which requires that related passages are encoded well enough to be integrated, is negatively associated with mind wandering (Smallwood et al., 2008). Taken with the broader literature on mind wandering, memory, and comprehension, the present findings suggest that people with less control over their attention should comprehend situation changes more poorly.

Relatedly, the individual differences in the relationship between sustained attention and subsequent memory observed are relevant to views on the role of executive functioning in interference susceptibility. A long-standing theoretical perspective proposes that people with poorer attention control, presumably from poorer functioning frontal lobes and interconnected brain regions, are more susceptible to interference from competing responses (e.g., Dempster & Corkill, 1999; Engle & Kane, 2004; Kane & Engle, 2002). Although sustained attention may only partly involve attention control, which is not always associated with interference resistance (Unsworth, 2019), the present findings are relevant to this perspective in showing that more self-reported focus during encoding was correlated with better resolution of competing responses. The most compelling evidence was shown in the comparisons of recent-response (D) recalls for groups in the upper and lower quartiles of overall on-task reports, which included people with the best and poorest sustained attention, respectively. The group with the best sustained attention showed proactive facilitation in overall recall of D responses, showing that the inclusion of otherwise competitive B responses, if anything, improved subsequent memory. These findings suggest that people who are better equipped to attend to and notice changes are more likely to avoid proactive interference, consistent with interference susceptibility views. However, research is needed to determine the extent to which a separate attention control construct contributes such individual variation in resistance to interference in episodic memory tasks.

Although the present experiment contributed new knowledge about the associations between attention during both A-B and A-D study and subsequent memory updating, it had limitations. We aimed to characterize how natural fluctuations in attention associated with memory updating, but our approach only afforded tests of correlational predictions from causal accounts. Future research could manipulate attention while including thought probes to verify attentional states and their associated recall dynamics. The present procedure also did not assess how stimulus features affected attentional states. We earlier showed that attention waned across exact repetitions and waxed upon changes (Garlitch & Wahlheim, 2020). This implicated roles for expectations and attentional capture consistent with findings suggesting that prediction errors can capture attention and improve memory (Bein et al., 2021; Stawarczyk et al., 2023). Further, we did not vary associative strength within pairs to determine how semantic features capture attention. People with lower working memory, which includes attention control, are less able to prevent interference from strong associates when learning weak associates (Rosen & Engle, 1998); therefore, strong associations may better capture attention. Future research could assess the roles of these stimulus features on attention during study by manipulating repetition frequency of A-B pairs as well as the semantic associations within and between A-B and corresponding A-D pairs. Finally, the theoretical framing here focused on the distinction between integration and interference views, but perspectives, such as neural differentiation are also relevant to consider. We set those matters aside here to avoid overcomplicating this already substantial contribution. However, we acknowledge the value in conducting future experiments combining neural and behavioral measures to disentangle the contributions of integration and differentiation to the memory benefits associated with self-reported attention to event changes.

Other limitations pertain to the use of thought probes to measure attention. As noted in the Method section, the two-choice (on-task / off-task) thought probe format does not allow participants to indicate when they thought about the task, but were not "on task" per se. These task-related thoughts can interfere with performance (Matthews et al., 1999; Smallwood et al., 2003). Studies comparing probe methods have shown that including an option to report task-related interference (TRI) states disproportionately decreases on-task report rates (Kane et al., 2021; Robison et al., 2019). Consequently, the present study likely overestimated sustained attention and underestimated its associated memory advantages. However, given the sensible associations observed here, this limitation of the two-choice method seemed inconsequential. To verify this, future studies could replicate key aspects of the current procedure and compare two-choice probes with other formats including the TRI option. Moreover, the susceptibility of self-reports to subjectivity may have also led to imprecise estimates of attention. An obvious solution is to manipulate attention; however, this undermines the ability to capture individual differences in sustained attention. Future studies may use converging indirect methods such as reaction time (deBettencourt et al., 2018), eye fixations (e.g., Krasich et al., 2018; Zhang et al., 2021), pupil dilation (e.g., Miller & Unsworth, 2019, 2021; Unsworth & Robison, 2018), and component waveforms of event related potentials and spectral markers (for a review, see Kam et al., 2022). Finally, presenting probes after study trials may disrupt encoding processes that continue during interstimulus intervals, leading to poorer memory, as suggested here by the significantly and nominally lower levels of memory performance for probed than unprobed A-B, A-D pairs. Such disruptions may have led on-task reports to reflect less attentive encoding states, thus weakening potential associations between sustained attention and memory for probed A-B, A-D pairs. However, there were also clear associations between on-task reports for probed items and memory performance for all unprobed item types, suggesting that this concern was minimal.

In conclusion, the present experiment replicated prior findings showing that self-reported attention to changed events was associated with subsequent memory for those events, that they changed, and what they changed from. This association was generally stronger when participants also reported attending to earlier events from which the recent events changed. However, lapses in attention to earlier events were also associated with better memory for recent events. Overall, predictions from integration and interference accounts were at least partly supported, with the MFC framework being most compatible with the collection of findings. This suggests that both mechanisms can be involved in memory updating, and that their influence may depend on how people sustain their attention in the service of detecting and subsequently recollecting changes.

CRediT authorship contribution statement

Christopher N. Wahlheim: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jennifer L. Fiedler:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Sydney M. Garlitch:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Blaire J. Weidler:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to my data/code.

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