Brief Communication

Binding among select episodic elements is altered via active short-term retrieval

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Of the many elements that comprise an episode, are any disproportionately bound to the others? We tested whether active short-term retrieval selectively increases binding. Individual objects from multiobject displays were retrieved after brief delays. Memory was later tested for the other objects. Cueing with actively retrieved objects facilitated memory of associated objects, which was associated with unique patterns of viewing behavior during study and enhanced ERP correlates of retrieval during test, relative to other reminder cues that were not actively retrieved. Active short-term retrieval therefore enhanced binding of retrieved elements with others, thus creating powerful memory cues for entire episodes.

[Supplemental material is available for this article.]

Active engagement during learning benefits long-term memory. For instance, actively controlling viewing of object arrays facilitates later memory relative to passive viewing (Voss et al. 2011a, b, c). Furthermore, numerous studies have demonstrated superior memory of paired-associates in a long-term retrieval test versus those that were simply restudied (Landauer and Bjork 1978; Thompson et al. 1978; Carrier and Pashler 1992; Karpicke and Roediger 2008). Despite considerable research on ramifications of active retrieval for subsequent memory, little is known regarding how active-retrieval changes the nature of memory representations (Bridge and Paller 2012). The majority of active-retrieval studies have examined memory for tested versus restudied paired-associates (Landauer and Bjork 1978; Carrier and Pashler 1992; Karpicke and Roediger 2008), without considering the relationship between the tested information and other untested information encountered during retrieval events. It is possible that active retrieval of one episode element promotes integration/binding of that item with other elements from the same episode. Thus, when the retrieved material is later encountered, it serves as a superior reminder cue for the other studied information. It is alternatively possible that active retrieval promotes general encoding of the retrieved information and co-occurring information, such that memory of all episode elements is nonspecifically enhanced, irrespective of which element is later used as the retrieval cue.

We recently demonstrated that active retrieval alters the contents of memory that are currently active and available for binding with associatively novel information, thus shaping later memory (Bridge and Voss 2014a, b). However, these previous studies did not test whether active retrieval causes disproportionate binding between the actively retrieved elements and other elements from the same episode, which would enable these actively retrieved elements to later serve as powerful retrieval cues to recall associated episode elements. Here, we tested whether episode elements that are targets of short-term retrieval become disproportionately strong retrieval cues for the other episode elements.

During study, subjects viewed three objects at distinct locations on a grid (Fig. 1; see Supplemental Methods for additional details). One object-location was randomly selected for either
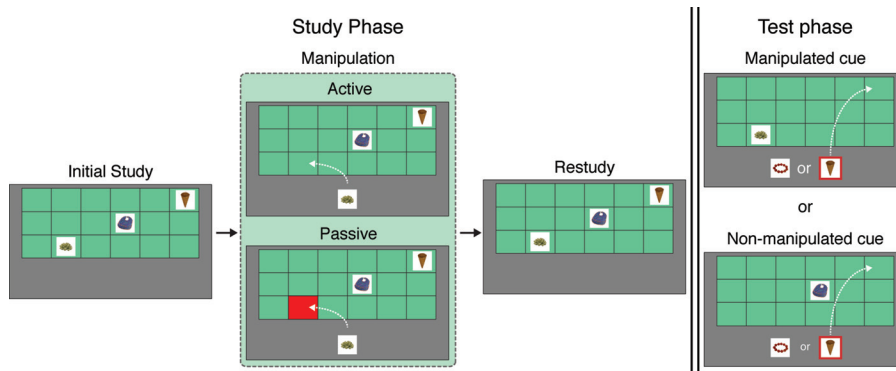
short-term retrieval (Active manipulation) or re-exposure (Passive manipulation). Subjects were later given a test on a subset of the nonmanipulated objects. There were four types of reminder cues at test: a manipulated or nonmanipulated object from either the Active or Passive condition. These reminder cues were used to prompt recall of the other object-locations studied during the original episode. Subjects first selected the associated nonmanipulated object (given two choices, one target and one equally familiar foil) for the associative recognition test and then recalled the nonmanipulated object's associated location for the spatial recall test. We predicted that memory of nonmanipulated objects would be enhanced when the reminder cue was a manipulated object in the Active condition (i.e., retrieved object) compared with all other conditions (i.e., when reminder cues were manipulated objects in the Passive condition or nonmanipulated objects in either the Active or Passive condition). This pattern would indicate that actively retrieved elements are particularly salient cues for the other episodic content.

Associative recognition performance did not differ across conditions (see Supplemental Results for discussion), whereas the type of reminder cue influenced accuracy of object-location recall, measured as the proportion of objects placed in either the correct location or an adjacent grid location at test (Supplemental Methods). There was a significant interaction of condition (Active/Passive) and cue type (manipulated/nonmanipulated) $[F_{(1,30)} = 8.58, P = 0.006]$ (Fig. 2A) and a main effect of cue type $[F_{(1,30)} = 4.64, P = 0.039]$, driven by superior recall given manipulated cues in the Active condition. For the Active condition, accuracy was significantly higher given manipulated versus nonmanipulated cues $[t_{(30)} = 3.54, P = 0.001]$, whereas accuracy did not differ by cue type in the Passive condition $[t_{(30)} = 1.16, P > 0.255]$. Furthermore, accuracy was higher given manipulated cues from the Active condition compared with manipulated cues from the Passive condition $[t_{(30)} = 2.08, P = 0.046]$. Accuracy did not differ given nonmanipulated cues from the Active versus

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Figure 1. Experiment overview. During the Study Phase, subjects initially studied three objects in different locations on a grid. Then, one of the objects was subjected to an Active or Passive manipulation. In the Active condition, subjects were prompted to recall the object's associated location and move it accordingly. In the Passive condition, subjects were given a visual cue indicating the object's associated location and were prompted to simply move the object to its location on the grid. Immediately following the manipulation, subjects restudied all three objects in their locations. Later during Test, subjects were given either a manipulated object cue or a nonmanipulated object cue and were prompted to select the associated object and then move it to its location on the grid. Each tested object was tested in only one manipulated cue condition (manipulated cue or nonmanipulated cue condition). Tested objects appeared twice at test: once as the associatively old object choice and once as a lure.

Passive conditions [$t_{(30)} = 1.77$, $P = 0.087$]. Finally, the main effect of manipulation condition was not significant [$F_{(1,30)} = 0.15$, $P > 0.705$], suggesting that short-term active retrieval of one element did not indiscriminately promote memory of the object array, but instead memory was selectively enhanced when actively retrieved objects served as reminder cues. An additional analysis of object-location recall using raw distance error yielded similar results (Supplemental Results). These findings indicate that manipulated objects in the Active condition served as disproportionately strong reminder cues for the associated nonmanipulated object-locations relative to other cue types (Active nonmanipulated cues and Passive manipulated and nonmanipulated cues).

We tested whether cueing with Active manipulated objects during the test phase produced unique event-related brain potential (ERP) correlates of successful memory retrieval (see Supplemental Methods for ERP analysis details). We hypothesized that cueing memory with the actively retrieved objects would enhance late-onset positive ERP correlates of retrieval, as these ERPs have previously been associated with recollective processing (Rugg and Curran 2007). Indeed, mean ERP amplitudes corresponding to successful memory given manipulated cues were significantly more positive than amplitudes given nonmanipulated cues at posterior sites during 500–700 msec (Fig. 2B) [$F_{(1.84,35.02)} = 3.61$, $P = 0.041_{GG}$] for the Active condition. This interaction of cue type and region reflected differences for manipulated/nonmanipulated cues that were significant for the occipitoparietal region [$t_{(19)} = 3.00$, $P = 0.007$] and marginally for the centroparietal region [$t_{(19)} = 1.78$, $P = 0.091$], but not at any other region (P values >0.310). We speculate that these effects on ERPs reflect robust retrieval of all objects from an episode given actively retrieved object cues, given that this pattern was observed for object-location recall accuracy and that similar ERP effects have been associated with recollection-related processing in many previous studies (Rugg and Curran 2007). None of these ERP differences for manipulated versus nonmanipulated cues were identified for the Passive condition for the 500–700-msec latency interval (P values >0.422) (Fig. 2C).

We monitored viewing behavior during study (Initial Study and Restudy) to evaluate possible mechanisms of the increase in cueing ability for the actively retrieved objects (see Supplemental Methods for eye tracking details). Object viewing did not differ

among conditions during Initial Study (Supplemental Results). Instead, the timecourse of viewing the manipulated object during Restudy (relative to Initial Study baseline) differed significantly between the Active and Passive conditions across the 1000-msec latency intervals that were tested [$F_{(2.77,74.77)} = 7.72$, $P < 0.0001_{GG}$] (Fig. 3A).

For the first 1000-msec interval, the proportion increase in viewing the manipulated object (Restudy relative to Initial Study) was significantly greater for the Active relative to the Passive condition [$t_{(27)} = 3.29$, $P = 0.003$]. For both conditions, the proportion of viewing increased for Restudy relative to Initial Study [Active Restudy $M = 0.51$, Initial Study $M = 0.32$, $t_{(27)} = 7.75$, $P < 0.0001$; Passive Restudy $M = 0.43$, Initial Study $M = 0.33$, $t_{(27)} = 5.88$, $P < 0.0001$]. Therefore, subjects viewed the manipulated object more during the first second of Restudy than during Initial Study in both Active and Passive conditions. However, this increase was significantly greater for the Active relative to the Passive condition.

For 1001–2000 msec, the proportion change in viewing the manipulated object was significantly lower for the Active relative to the Passive condition [$t_{(27)} = 3.00$, $P = 0.005$]. For the Active condition, viewing of the manipulated object decreased for Restudy relative to Initial Study [Restudy $M = 0.26$, Initial Study $M = 0.37$, $t_{(27)} = 4.01$, $P < 0.001$], whereas there was no significant change for the Passive condition [Restudy $M = 0.32$, Initial Study $M = 0.35$, $t_{(27)} = 1.92$, $P = 0.064$]. Therefore, subjects viewed the manipulated object less during Restudy relative to Initial study for the Active condition only. Furthermore, viewing of the manipulated object decreased during this interval significantly more in the Active relative to the Passive condition. The change in viewing did not differ for the Active versus Passive conditions for any of the subsequent latency intervals (spanning 2001–4000 msec; P values >0.255). An additional analysis indicated that these effects on viewing behavior were timecourse-specific, as they were not observed when measuring overall viewing time (Supplemental Results).

Manipulation during study thus significantly influenced the timecourse of viewing behavior, with more viewing of the manipulated object in the Active condition during the first second of Restudy followed by relatively less viewing of this object (and thus relatively more viewing of other nonmanipulated objects) during the 1001–2000-msec interval. It is notable that during this interval, viewing switched from the manipulated object to the nonmanipulated objects, particularly for the Active condition. An additional analysis indicated that it was not the case that selectively increased viewing of the later-tested nonmanipulated objects during this interval produced superior later memory (Fig. 3B; Supplemental Results). Eye-movement findings therefore indicate that a unique pattern of viewing manipulated objects followed by nonmanipulated objects occurred in the Active condition, and was thus related to superior later memory cueing ability of Active manipulated objects. Trivial factors such as overall viewing/attention of both manipulated and later-tested objects were not uniquely associated with the effects of the manipulation (Supplemental Results).

We next evaluated whether the unique viewing behavior during Restudy in the Active condition was predictive of the
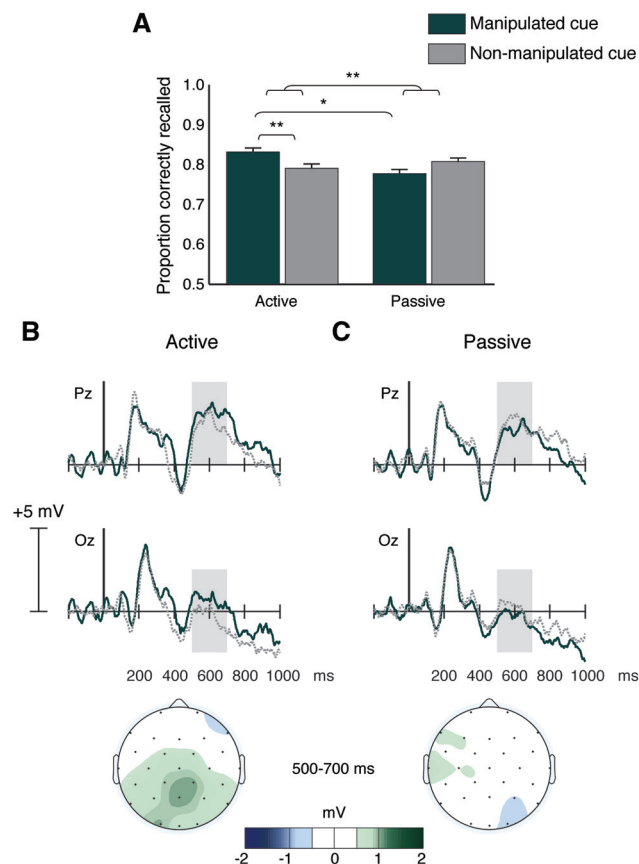
Figure 2. Active-retrieval selectively modulates cueing efficacy and ERP correlates of retrieval. (A) The proportion of correctly recalled object-locations increased selectively when Active manipulated objects were used as cues, suggesting that Active retrieval promoted dominance of these objects due to disproportionate binding with the other nonmanipulated objects. (B) Active manipulated cues exhibited enhanced positivity between 500 and 700 msec relative to nonmanipulated cues. These results suggest that manipulated object cues in the Active condition modulated retrieval-related neural processing. (C) ERPs for the Passive condition do not differ between manipulated and nonmanipulated cues. Error bars indicate standard mean error. (**) $P < 0.01$, (*) $P < 0.05$.

further suggest that greater ERP signals of memory retrieval for Active manipulated cues were not simply a reflection of greater viewing of these cues during Restudy.

To evaluate the 1001–2000-msec interval, we extracted trials that demonstrated low viewing of the manipulated object during this interval (determined by median split of viewing durations) for the manipulated cue condition and compared ERPs across the Active and Passive conditions (Fig. 3D). Mean amplitudes were significantly higher for the Active relative to the Passive condition at centroparietal [$t_{(15)} = 2.75$, $P = 0.015$] and occipito-central sites [$t_{(15)} = 2.63$, $P = 0.019$]. These results suggest that viewing behavior during the 1001–2000-msec interval in the Active condition was associated with binding the manipulated
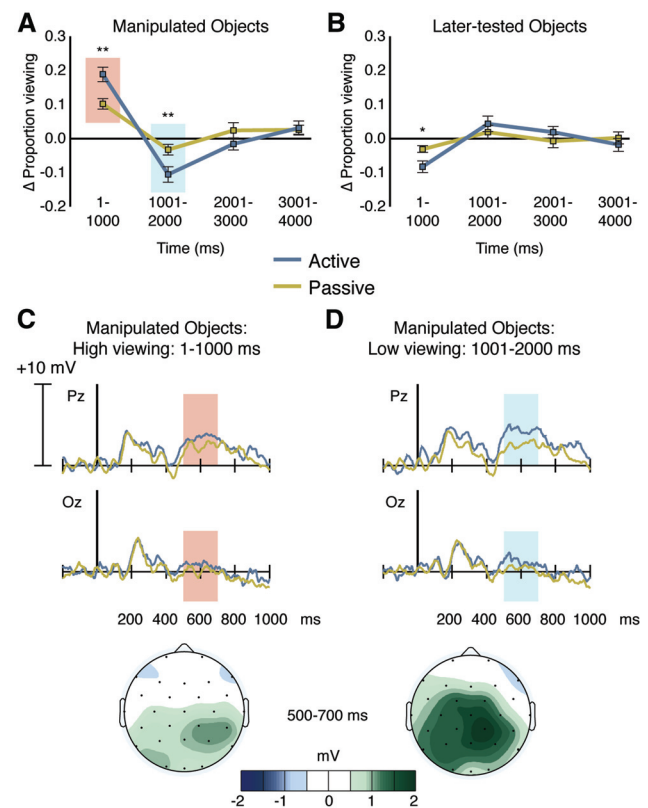
Figure 3. Eye movements are modulated following Active short-term retrieval during Restudy and correspond to late-positive ERPs at test. (A) The Active/Passive manipulation significantly modulated viewing of the manipulated object. For both conditions, viewing increased from Initial Study to Restudy between 1 and 1000 msec; however, this effect was more pronounced for the Active condition (highlighted in red). Between 1001 and 2000 msec, viewing selectively decreased from Initial Study to Restudy for the Active condition only (highlighted in blue). (B) Viewing the later tested nonmanipulated object significantly decreased between 1 and 1000 msec for the Active relative to the Passive condition. Viewing did not differ across conditions or phases for any of the later time intervals. (C) ERPs during Test corresponding to high viewing of the manipulated objects during 1–1000 msec of Restudy did not significantly differ across the Active and Passive conditions. This early eye movement effect and corresponding ERP effects are highlighted in red in (A,C). (D) ERPs corresponding to low viewing of the manipulated objects during 1001–2000 msec of Restudy were significantly more positive between 500 and 700 msec for the Active relative to the Passive condition. This eye movement effect and corresponding ERP effects are highlighted in blue in (A,D). These results indicate that viewing behavior during 1001–2000 msec of Restudy modulated retrieval-related neural processing at test. Error bars indicate standard mean error. (**) $P < 0.01$, (*) $P < 0.05$.

ERP signals of cued retrieval at test (Fig. 3C,D). The two aspects of viewing behavior during Restudy associated with the Active condition (more than the Passive condition) included greater viewing of the manipulated object (at the expense of the other objects) during the first 1000-msec interval followed by less viewing of the manipulated object (and thus more viewing of the other objects) during the 1001–2000-msec interval (Fig. 3A). We therefore tested for associations between each of these two aspects of viewing behavior and ERP correlates of retrieval (Supplemental Methods).

To evaluate associations for the 1–1000-msec interval, we extracted trials that demonstrated high viewing of the manipulated object during this interval (determined by median split of viewing durations) for the manipulated cue condition and compared ERPs across the Active and Passive conditions (Fig. 3C). Mean amplitudes did not differ significantly across conditions at either centroparietal or occipitoparietal sites (P values >0.277). Therefore, the first second of viewing may have been involved in the unique memory processing that occurred in the Active condition, but it was not critical for later retrieving the other objects when an actively retrieved object served as a reminder cue. These results

object to the nonmanipulated objects, as indicated by enhanced ERP correlates of recollection. That is, because this viewing behavior selectively predicted enhanced retrieval-related neural correlates at test, it is directly related to the enhanced binding that occurred for Active manipulated objects at study. Importantly, the manipulated object that was later used as a cue (the ERP time-locking event) was viewed less during this Restudy interval, with disproportionately greater viewing of the nonmanipulated objects. We hypothesize that greater posterior late-positive amplitudes given the manipulated-object cue in the Active condition reflected heightened retrieval of the entire episode due to stronger binding of all objects with the manipulated object.

Importantly, it is not merely the case that greater attention to objects led to the observed behavioral effects. Manipulated objects in the Active and Passive conditions were both at the spotlight of subjects' visuospatial attention, yet beneficial influences on memory were selective for manipulated objects in the Active condition. In addition, overall viewing of manipulated objects was matched during the Restudy period for the Active and Passive conditions. Instead, the timecourse of object viewing was unique to the manipulated objects in the Active condition. We speculate that the actively retrieved object became dominant in working memory (Lewis 1979) during the first 1000 msec of Restudy when it was viewed heavily, and remained so while subjects directed their gaze to the other nonmanipulated objects during the 1001 to 2000-msec interval. This could have increased binding of the actively retrieved object to all others and enhanced ERP correlates of retrieval later during test.

These findings are novel in showing that not all episode elements cue retrieval equally and that the memory-enhancing effects of short-term testing are not equally distributed among all elements of an episode. In one prior study, objects were better later retrieval cues than were their coloration or location (Starns and Hicks 2008), suggesting that different stimulus features may serve as preferential reminder cues. The current findings expand on this idea by showing that the efficacy of reminder cues can be increased selectively for specific objects, all other things being equal. Specifically, we show that active short-term retrieval of select elements can facilitate subsequent retrieval of other associated elements. In this sense, it can be said that these actively retrieved episodic elements achieve relative "dominance" within the representation, such that binding of dominant elements with others is stronger than binding that occurs among other nondominant elements. This finding is consonant with our previous studies using active-retrieval manipulations, in which we have found that actively retrieved memory content can be preferentially bound with associatively novel information, thus shaping the information that is learned and later remembered (Bridge and Paller 2012; Bridge and Voss 2014a, b).

We previously demonstrated that active retrieval, relative to passive re-exposure, modulates the contents of subsequent memory (Bridge and Voss 2014a, b). In Bridge and Voss (2014b), subjects studied objects in specific locations on a background context scene. Then, subjects were asked to recall each object's location on a new background scene. The recalled locations always diverged from the original locations to some extent. On a final recognition test, subjects selected the recalled locations in favor of the original studied locations, even when the recognition test occurred on the original background context scene. This updating effect did not occur in a passive re-exposure condition, in which subjects maintained the original studied locations. Therefore, active retrieval caused the updated object-location associations to bind with the original context background scenes, even though they had never been physically paired. Interestingly, hippocampal activity was associated with this binding of object-locations

with background scenes that were associatively novel. The current results show that active retrieval not only modulates binding between memory content and associatively novel information, but also causes disproportionately strong binding for the actively retrieved elements to other elements from the same episode. Although we cannot conclude that the ERP correlates of dominance-cued retrieval in the current study originate from hippocampus, the nature of the arbitrary relational binding that was enhanced by the active-retrieval manipulation is strongly suggestive of hippocampal contributions (Eichenbaum and Cohen 2001; Bridge and Voss 2014b).

Contrary to the view that the hippocampus binds elements obligatorily and automatically (Olsen et al. 2012), we provide evidence suggesting that some elements are relatively dominant owing to increased binding during study. Future research could determine whether bindings among elements are nonreciprocal in addition to being nonequipotent. This knowledge could be integral to determining how memory representations are structured and how specific memory elements and their interrelationships may be targeted for modification.

Acknowledgments

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