Active math and grammar learning engages overlapping brain networks

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We here demonstrate common neurocognitive long-term memory effects of active learning that generalize over course subjects (mathematics and vocabulary) by the use of fMRI. One week after active learning, relative to more passive learning, performance and fronto-parietal brain activity was significantly higher during restesting, possibly related to the formation and reactivation of semantic representations. These observations indicate that active learning conditions stimulate common processes that become part of the representations and can be reactivated during retrieval to support performance. Our findings are of broad interest and educational significance related to the emerging consensus of active learning as critical in promoting good long-term retention.

Results

In experiment (Exp.) 1 \((n = 86)\), the participants learned foreign language vocabulary by a more passive strategy (study [S]) and by active RP. In Exp. 2, a subsample \((n = 72)\) of the participants from Exp. 1 were required to actively generate the mathematical solution (CMR) (e.g., refs. 4, 5) or more passively imitate a provided algorithmic solution (AR) (Fig. 1A–D). Commonalities in brain activity for the active learning methods were assessed in a conjunction analysis \((\text{RP} \cap \text{CMR} > \text{AR})\) (9) of functional MRI (fMRI) data acquired about 1 wk after initial learning. After this retention interval, several major consolidation processes have occurred (10) and the performance should largely reflect long-term memory. In both experiments, performance was higher after active than passive learning [Exp. 1: \(\text{RP} = 40\%\); \(\text{S} = 25\%\) (11); Exp. 2: \(\text{CMR} = 49\%\); \(\text{AR} = 44\%\) (12)].

For both active learning methods, relative to passive learning, higher brain activity was found in a number of cortical regions when participants were tested on the same questions 1 wk later, notably in the left hemisphere (Fig. 2A and B). The regions included the inferior frontal gyrus (IFG) \((x,y,z = -42,44,8; -36,52,12)\), precuneus \((x,y,z = -8,72,42)\) inferior parietal/angular gyrus \((x,y,z = -44,-58,52,-34,-58,38)\), frontal superior medial \((x,y,z = -8,16,44;-6,30,36)\), the posterior cingulum \((x,y,z = -2,-30,32)\), and a smaller cluster within the IFG \((x,y,z = -34,16,32)\). Despite the observation that regions C1–C6 had higher brain activity when learning with active methods, there were two regions that had disproportionally higher activity when learning math (Fig. 2B, C1 and C3). Next, to verify that the results were not driven by the higher performance rate following active learning, we reran the imaging analysis and statistically controlled for performance differences between active and passive learning. The results remained virtually identical, suggesting that the observed differences predominantly reflected qualitative active learning processes and not merely quantitative performance differences. Reversing the contrast (i.e., \(S > \text{RP} \cap \text{AR} \cap \text{CMR}\)) revealed no common brain activity that was stronger for the two passive vs. active learning methods.

Discussion

Our findings provide support for the hypothesis of engagement of a shared brain network at retrieval after active compared to more passive learning. Specifically, 1 wk after learning, despite identical retrieval conditions, higher functional brain activity was evident after active compared to more passive initial learning of vocabulary and mathematics in several left-lateralized brain regions, notably in the precuneus, the inferior parietal cortex/angular gyrus, and the left lateral and medial PFC.

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The observed overlap in brain activity during retrieval of vocabulary and mathematics may reflect reactivation of common active learning processes. Such processes could be reactivation of semantic representations by the left PFC (7), reactivation of active learning processes. Such processes could be reactivation of vocabulary and mathematics may reflect reactivation of common curriculum-specific processes (15). With this caveat, consistent with a constructivist perspective, our findings suggest that active learning of vocabulary and mathematics stimulate common processes that become part of the representations and can be reactivated during retrieval to support performance.

In conclusion, our results support the hypothesis of a common brain basis of learning effects following active vs. more passive learning of two separate course subjects, vocabulary and mathematics. These results are of importance for educators as well as the broader society (1–3), as they provide mechanistic insights into how activity improves student performance via differential brain engagement during learning.

**Materials and Methods**

The same upper-secondary school pupils participated in Exps. 1 and 2 (Mage = 18.2 y). In experiment 1, the pupils learned foreign language vocabulary (word pairs), by means of RP (active) and by means of study (S, passive). In experiment 2, the pupils learned to solve mathematical problems by means of CMR (no solution formula was provided, active; 4, 5) or through AR (a solution formula was provided, passive; 4, 5). One week later, participants returned to take a subsequent memory test of all of the previously learned materials in the MR scanner (Fig. 1 C and D). In both experiments, each student saw a random order of questions and whether a question was learned through active or passive methods was also random.

A conjunction analysis investigated whether the two active learning conditions engaged common brain regions (11) (i.e., the “conjunction null” hypothesis; see SI Appendix). For each experiment, respectively, the minimum of the t values in each voxel was calculated (Exp. 1: RP > S, Exp. 2: CMR > AR). The statistical threshold was set to t > 3.5 at the voxel level, and k > 10 at the cluster level. An extended materials and methods section can be found in SI Appendix.
Data Availability. The anonymized data (fMRI) that support the results from the current study have been deposited in XNAT Central [https://central.xnat.org; project ID ActiveMathGram (16)].

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