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Fast mapping rapidly integrates information into existing memory networks

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Abstract

Successful learning involves integrating new material into existing memory networks. A learning procedure known as fast mapping (FM), thought to simulate the word-learning environment of children, has recently been linked to distinct neuroanatomical substrates in adults. This idea has suggested the (never-before tested) hypothesis that FM may promote rapid incorporation into cortical memory networks. We test this hypothesis here in two experiments. In our first experiment, we introduced fifty participants to sixteen unfamiliar animals and names through FM or explicit encoding (EE), and tested subjects on the training day, and again after sleep. Learning through EE produced strong declarative memories, without immediate lexical competition, as expected from slow-consolidation models. Learning through FM, however, led to almost immediate lexical competition, which continued to the next day. Additionally, the learned words began to prime related concepts on the day following FM (but not EE) training. In a second experiment, we replicated the lexical integration results, and determined that presenting an already-known item during learning was crucial for rapid integration through FM. The findings presented here indicate that learned items can be integrated into cortical memory networks at an accelerated rate through fast mapping. The retrieval of a known related concept, in order to infer the target of learning, is critical for this effect.

Keywords: *fast mapping, encoding, learning, lexicon, memory*

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

Our memories do not exist in isolation. Information that we learn becomes integrated with existing knowledge, allowing us to access relevant memories in the future. The process of consolidating newly encountered information is typically gradual, benefiting from time (Frankland & Bontempi, 2005; McClelland, McNaughton, & O'Reilly, 1995) and frequently sleep (e.g., Coutanche, Gianessi, Chanales, Willison, & Thompson-Schill, 2013; Stickgold & Walker, 2005). A key model of human memory –the complementary learning systems (CLS) framework– can account for gradual consolidation by proposing that learned items are first rapidly encoded (by the hippocampus), and then gradually integrated into long-term memory networks (in the neocortex; McClelland et al., 1995). Like the acquisition of semantic memory, word learning is associated with a slow and sleep-assisted consolidation process (e.g., Tamminen & Gaskell, 2013; Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010), suggesting that similar principles underlie integrating these types of information (Davis & Gaskell, 2009).

What is the functional consequence of a word becoming ‘integrated’ into a memory network? One common prerequisite is that an integrated memory should, when activated, produce activation for neighboring items in the network. This kind of cross-item influence can be observed in participants’ response times: Learning a spoken (Gaskell and Dumay, 2003; Leach & Samuel, 2007) or written (Bowers, Davis, & Hanley, 2005) word can slow responses to pre-existing words that are phonologically or orthographically similar to the new word, reflective of spreading activation within the network. Notably, this effect does not occur immediately, and instead typically emerges on the days following training (e.g., Davis, Di Betta, Macdonald, & Gaskell, 2009; Dumay & Gaskell, 2007; Dumay & Gaskell, 2012; Tamminen et al., 2010; also see Lindsay and Gaskell, 2013, for the impact of interleaving). Sleep-related mechanisms appear to typically support this process, as neural oscillations in post-learning sleep can predict the magnitude of subsequent lexical competition (but not declarative memory; Tamminen et al., 2010). This result argues that lexical competition can be observed once newly learned words are “consolidated into neocortical representations” (p. 3779, Davis & Gaskell, 2009).

Outside the laboratory, we are not typically explicitly taught new words, but instead encounter them in the context of other items, and then infer their meaning. A learning procedure known as ‘fast mapping’ (FM) draws on this principle by presenting the image of a concept alongside a known item, with a perceptual question containing the new item’s name (e.g., “Are the torato’s antennae pointing up?” with images of an unknown insect and a cricket). Retrieving

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

and ruling-out the cricket allows the learner to infer that the new word refers to the novel item (Halberda, 2006). Fast mapping has been hypothesized to underlie rapid vocabulary learning in infancy (Bloom & Markson, 1998; Carey & Bartlett, 1978); supported by findings that 2-year olds can fast map novel nouns during a single exposure (Spiegel & Halberda, 2011).

Recently, an investigation of adult learning raised the possibility that FM and explicit encoding (EE) may draw on distinct neuroanatomical substrates (Sharon, Moscovitch, & Gilboa, 2011; although also see Smith, Urgolites, Hopkins, Squire, 2014). This study reported that although (as expected) patients with hippocampal damage could not learn words for unknown items through EE, they could learn the items' names through FM. This striking result led to an explanation with two components: that FM might bypass the hippocampal system, and that FM might rapidly incorporate new concepts into cortical memory networks (Sharon et al., 2011). The first possibility –nonhippocampal learning– fits with prior reports that some patients can learn new words despite having substantial hippocampal damage (although they require many repetitions; Bayley & Squire, 2002; Gordon Hayman, Macdonald, & Tulving, 1993; O'Kane, Kensinger, & Corkin, 2004; Skotko et al., 2004). Given the extensive hippocampal damage in some of these learners (e.g., E.P. in Bayley & Squire, 2002), they likely employ a non-hippocampal learning process (Bayley & Squire, 2002; Gordon Hayman et al, 1993; O'Kane et al., 2004).

Here, we test the second claim: that FM produces rapid cortical consolidation. If FM integrates new material directly into memory networks, we would expect that items learned through FM would show evidence of integration soon after learning, without needing the prolonged consolidation process commonly associated with EE. We tested this hypothesis by testing for signs of lexical and semantic integration of new words after FM. In two experiments, we presented participants with sixteen unfamiliar animals and associated new words. In Experiment 1, we presented items through a FM or EE procedure and measured both declarative memory and lexical integration. We also took the opportunity to examine semantic integration. Many studies of lexical integration have employed words without associated meanings (e.g., Bowers et al., 2005), although outside the laboratory words typically represent concepts. Indeed, the FM procedure itself involves inferring a word's meaning from presented images. Investigations have rarely tested integration at both the lexical (e.g., 'torato' is close to 'tomato') and semantic ('torato' is close to cricket) levels (although see Clay, Bowers, Davis, & Hanley,

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

2007). We therefore also asked if FM impacts the typical timeline for integrating a word's *meaning* into memory (Tamminen & Gaskell, 2013). Experiment 2 repeated the lexical and declarative memory conditions (with slight variations) and introduced a hybrid condition designed to identify key components of the FM procedure.

Method

Experiment 1

Participants

Fifty participants (14 males; mean (M) age = 22.3, standard deviation (s.d.) = 3.9; all English speakers; no known learning or dyslexia impairments) were randomly assigned to FM or EE learning conditions. Participants were recruited until each group contained twenty-five participants who attended both the first and second session. We obtained informed consent from all participants each time they entered the lab. Participants were compensated for their time. The University of Pennsylvania Institutional Review Board approved all procedures.

Materials and Design

We presented participants with sixteen little-known animals (which were the least familiar of a superset that was evaluated by an independent norming group). We verified that the animals were unfamiliar to participants at the end of the study, by asking how familiar they had been with each animal before the study on a 1-7 scale. Trials associated with any animal that was given a rating higher than three were removed from the analyses of all tasks for that participant. If a participant rated more than half the animals as this familiar, a replacement participant was run until each condition contained twenty-five subjects. As expected from random assignment, the groups did not differ in prior familiarity with the animals ($t(47) = 0.15$, $p = 0.88$).

An established approach to measuring the lexical integration of a new word is to examine response-times to existing words that are lexical neighbors of the new word. We drew on the finding that participants' responses to 'hermit' words (which have no letter substitution, transposition, deletion or addition neighbors; e.g., 'tomato') are slowed once these words become 'non-hermits' (due to learning a new similar word; e.g., 'torato'; Bowers et al., 2005). In order to later measure lexical competition in this study, we therefore employed fictional names for the new animals we presented; using sixteen of the novel words employed in Bowers and colleagues' (2005) original investigation (all low frequency; six letters; pronounceable), which were created by modifying one character of a hermit word (see Table 1). Each word was randomly allocated to one of the animals, but used consistently for all participants. Employing these (randomly allocated) constructed names also ensured that participants could not use existing knowledge to

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

successfully associate items and names in the subsequent associative recognition test (as discussed previously: Smith et al., 2014).

Procedure

Participants were randomly allocated to the FM or EE training condition. The two groups performed exactly the same set of tasks after training, so that any resulting group differences had to be due to differences in training.

Training: Participants in the EE condition viewed an image of each of the sixteen unfamiliar animals above an instruction to ‘Remember the X’ (where X = the animal’s constructed name; listed in Table 1). All images were closely cropped (i.e., contained no background) and were centrally placed on a white background (see Figure 1 for an example). Each image and associated text was displayed for six seconds, in a random order. After the sixteen animals were presented, the images and text were shown once more in a new random order.

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

Experiment 1	Experiment 2	
sleere (sleeve)	polato (potato)	sleere (sleeve)
viodin (violin)	fostil (fossil)	viodin (violin)
motaic (mosaic)	mearow (meadow)	walnot (walnut)
torato (tomato)	motaic (mosaic)	tartoo (tattoo)
tandon (tendon)	colfin (coffin)	tandon (tendon)
penble (pebble)	torato (tomato)	penble (pebble)
cedery (celery)	jergey (jersey)	balboo (bamboo)
dirsel (diesel)	garnic (garlic)	cedery (celery)
puncil (pencil)	ganaxy (galaxy)	dirsel (diesel)
nerdle (needle)	banara (banana)	fablic (fabric)
guitur (guitar)	teapit (teapot)	kidley (kidney)
cragle (cradle)	nerdle (needle)	puncil (pencil)
alazon (amazon)	guitur (guitar)	piltar (pillar)
pargel (parcel)	cragle (cradle)	alazon (amazon)
naskin (napkin)	amchor (anchor)	talmac (tarmac)
eramel (enamel)	holmet (helmet)	pargel (parcel)

Table 1: Stimuli employed in Experiments 1 and 2. The learned words were constructed from existing 6-letter hermit words (from Bowers et al., 2005). The generating hermit words (which were shown as part of the lexical competition task) are in parentheses after each stimulus. Experiment 2 employed a counterbalanced design, where for half the participants, the left set of words were associated with novel animals, and the right set were unlearned (control) items in the lexical competition task. The lists swapped roles for the remaining participants.

We introduced participants in the FM condition to the sixteen unfamiliar animals through a typical FM paradigm (e.g., as used in Sharon et al., 2011, with the distinction that we used constructed names as described above, and all animals, rather than animals, fruit, vegetables and flowers). Each new animal was presented next to an image of a well-known animal (from the same taxonomic class), with a perceptual question below that referred to the new animal by name (e.g., “Are the antennae of the Torato pointing up?”). The familiar animal also possessed the

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

feature in the question (e.g., antennae, although in the opposite state - e.g., pointing down), so that participants could not simply respond based on the presence of the feature alone.

Participants responded 'yes' or 'no' using a keyboard. The unfamiliar animal was equally likely to appear on the left or right, and the correct answer was equally likely to be 'yes' or 'no'. Each pair of images and question was presented for six seconds (matching the EE condition), in a random order. After the sixteen unfamiliar animals had been presented, they were presented once more in a new order. For the second presentation, each unfamiliar animal was paired with a new known animal and question, so that participants could not just remember their first answer. The screen-position of each image, and the correct answer, were reversed in the second presentation.

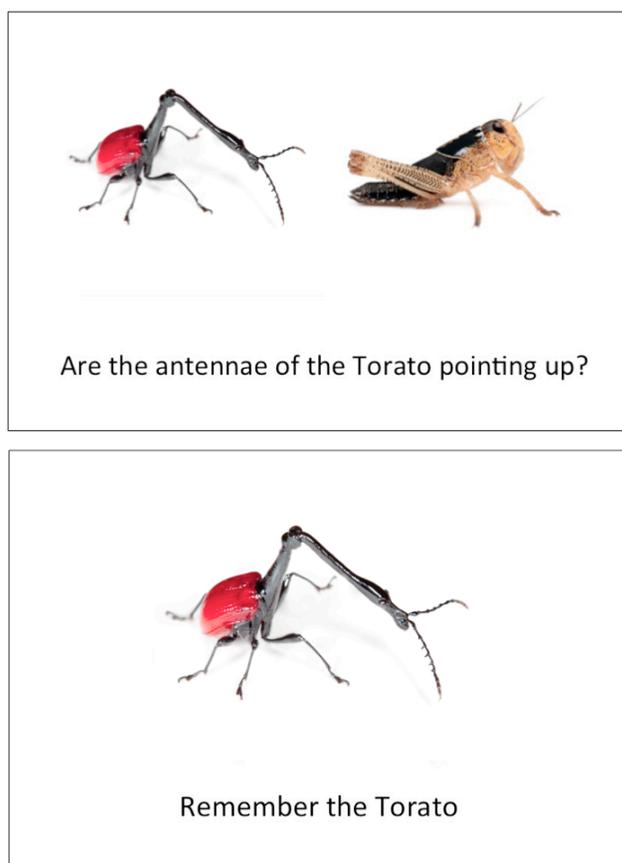


Figure 1: Example training trials for Experiment 1. A fast mapping (top) and explicit encoding (bottom) presentation of 'torato' (actually a giraffe weevil; *Trachelophorus giraffe*). Image of giraffe weevil shown with permission from the copyright holder (Alex Hyde; www.alexhydephotography.com).

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

Testing: Testing procedures were identical across the two groups. We assessed learning with tests in a fixed order (as presented below) on two days. The tests were completed ten minutes after training. Participants were given an unrelated vocabulary test and questionnaire during the training–testing interval to prevent verbal rehearsal. Participants returned for a second set of tests approximately 24 hours later. At the end of the second session, we assessed prior familiarity with the training stimuli, and, as part of the debriefing procedure, presented the animals’ actual names.

Declarative memory: We measured declarative memory using tests of both recall and recognition. At the start of the testing session, we asked participants to orally recall as many of the new animals’ names as they could. Next, participants identified which of three presented new animals (all in the training set, ensuring that familiarity alone would not help) belonged to each new name. Every animal acted as a foil for two other animals. Participants had six seconds to respond to the randomly ordered trials.

Lexical integration: We operationalized lexical integration with a response-latency measure of lexical competition, following the procedure of Bowers et al. (2005). Participants indicated whether a word referred to a man-made or natural item as quickly and as accurately as possible by pressing a key on the left or right of a keyboard (left/right key assignments were swapped for half the participants, and displayed at the bottom of the screen as a reminder). We presented 32 words: the 16 hermit words that had been used to create the learned words (e.g., ‘tomato’; Table 1), and 16 unused hermits from Bower et al. (2005). Each trial began with a fixation cross for 800 ms, followed by a blank screen for 350 ms, a word for 500 ms, and feedback (“Correct!” or “Incorrect.”) for one second. Response times were analyzed from correct trials after removing reaction times faster than 300 ms and slower than 1.5 s (as performed by Bowers et al., 2005). Lexical competition was measured as the difference in response times to hermits that were used to create the trained words (i.e., now ‘former hermits’), and hermit words that were not used in this way; any difference indicates that the learned words (e.g., torato) have affected the processing speed of their orthographic neighbors (e.g., tomato). One FM, and one EE, participant had below 70% accuracy on one of the days, and were removed from the response-time analyses (days 1 and 2 respectively).

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

Semantic integration: We operationalized semantic integration as a change in response latencies in semantic priming, following the procedure of Stickgold et al. (1999). Participants viewed pairs of words (prime followed by target) in the center of the screen, one after the other. Each prime was presented for 200 ms, followed by the target, which remained on-screen until a response was made. Participants were asked to read both items silently and to indicate whether the second was a real or false word as quickly as possible, by pressing a key on the left or right of a keyboard (left/right key assignments were swapped for half the participants; key reminders were shown at the bottom of the screen). Half the targets were real words. The trials were randomly ordered and separated by a 700 ms fixation cross. The task began with five (unanalyzed) practice trials. Semantic priming is measured as a response-time difference to target words that are preceded by semantically related words, compared to target words that are preceded by unrelated words. In our case, the ‘related’ pairs consisted of newly learned animal names priming already-known animals (from the same taxonomic class; different to the familiar animal used in the FM paradigm). For ‘unrelated’ pairs, the newly learned animals preceded already-known artifacts. The newly learned names served as primes, rather than targets, because the ‘word’ versus ‘nonword’ judgments would likely create unwanted conflict when responding to the new words (see Tamminen & Gaskell, 2013, for another example of this approach). We note that one consequence is that the priming-measure is also influenced by response-time differences to animals and artifacts, however because this was consistent across groups and testing-days, this did not directly drive our contrasts of interest. Response times were analyzed from correct trials only, after removing reaction times faster than 150 ms and slower than three standard deviations above the participant’s mean. We removed the response times of one FM participant with sub-70% accuracy on both days, and another who confused the keys on day 1 (giving 4% accuracy).

Experiment 2

Our second experiment had two goals: Firstly, we wanted to determine if the results from Experiment 1 are robust to several design modifications (more closely aligned with the protocol employed in Bowers et al., 2005). These changes are noted below. Secondly, we wanted to try to identify which of the many differences between the FM and EE conditions might underlie the rapid consolidation effect we observed in Experiment 1, by creating a third learning condition with features of each of the other two conditions. Specifically, we wanted to tease apart possible

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

effects of the incidental encoding question in the FM procedure, from effects of the inference process induced by having a known animal in each FM trial.

Participants

Sixty additional participants (15 males, M age = 21.5, s.d. = 2.2) were randomly allocated to one of three conditions: FM, EE or a new ‘Incidental Encoding’ (IE) condition (described below). Participants were recruited until each group contained twenty eligible participants. We obtained informed consent from all participants, who were compensated for their time.

Materials and Design

Participants were first presented with training trials according to their randomly assigned group. The FM and EE training conditions followed the same procedure as Experiment 1. A new IE condition contained features of the FM and EE conditions (Figure 2): IE participants responded to the same questions as the FM condition (e.g., “Are the antennae of the Torato pointing up?”), but with only the novel animal on-screen, like the EE condition. This combination separated the incidental nature of the encoding task (by employing the same question as FM) from inference (by not presenting an adjacent known item).

We verified that the learned animals were unfamiliar to participants in the same manner as Experiment 1: excluding animals rated above 3 out of 7 on an end-of-study questionnaire, and replacing participants who rated more than half the animals as familiar. Like Experiment 1, the groups did not differ in their prior familiarity with the animals ($F(2,57) = 0.26, p = 0.77$).

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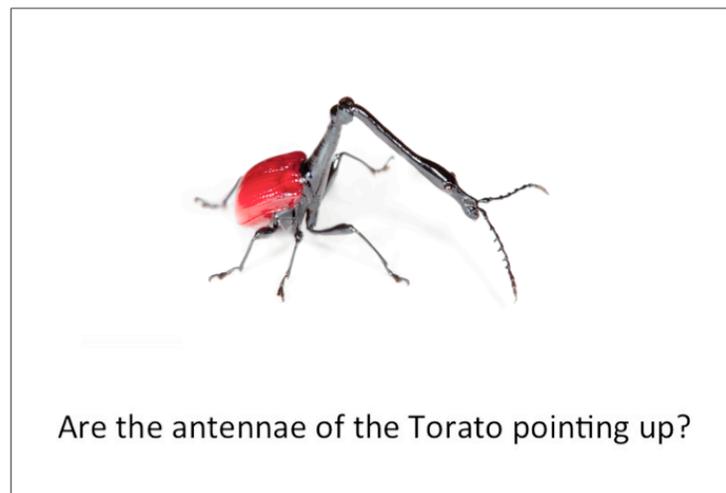


Figure 2: Example training trial in the Incidental Encoding condition. Image shown with permission from the copyright holder (Alex Hyde; www.alexhydephotography.com).

For Experiment 2, we counterbalanced which hermit words were used to generate animal names. Thirty-two hermit words from Bowers et al. (2005) were randomly split into two sets (Table 1). One set was used to generate the sixteen animals' names, while the others were comparison hermits in the lexical competition task. The role of each set alternated by participant, ensuring that any response-time differences did not depend on using particular words.

Testing: After a 10-minute delay (containing the same word tasks as Experiment 1), participants first received the lexical competition test followed by the forced-choice associative recognition test. This order (the reverse of Experiment 1) ensured the lexical competition results were not affected by any prior testing trials. For Experiment 2, we amended the lexical competition task to match the proportions of words used in Bowers et al. (2005). Specifically, in addition to the sixteen words used to generate the animal names, the trials included sixteen other hermits (counterbalanced, as described above) and thirty-two other six-letter words with similar frequencies as the hermits. Fifty percent of the words referred to natural entities, while the remainder were artificial (giving balance for the 'natural' versus 'artificial' task). Following the lexical competition task, participants responded to the associative recognition test (as described for Experiment 1), after which participants were debriefed, and familiarity for the animals was

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

assessed. We did not administer the semantic priming task again, as (based on the results of Experiment 1) we did not expect to find semantic priming immediately after training.

Results

Experiment 1

Participants who had learned names for novel animals through an EE procedure had superior declarative memory performance 10 minutes after training, compared to participants encountering the same names through FM (Figure 3): performance was superior in both recall (Mann-Whitney U test due to non-normality: $U = 103$, $p < 0.001$) and associative recognition ($t(1,48) = 4.43$; $p < 0.001$, $d = 1.25$) after EE (Recall: $M = 2.20$, range = 0-8; Recognition: $M = 80.7\%$, s.d. = 17.1%) compared to FM (Recall: $M = 0.24$, range = 0-2; Recognition: $M = 56.2\%$, s.d. = 21.8%). This continued to Day 2 for both recall ($U = 202$, $p = 0.03$; EE: $M = 2.32$, range = 0-9; FM: $M = 0.80$, range = 0-4) and recognition ($t(1,48) = 4.73$, $p < 0.001$, $d = 1.34$; EE: $M = 78.0\%$, s.d. = 19.3%; FM: $M = 57.0\%$, s.d. = 11.0%).

In contrast, the test of lexical integration showed the reverse effect (Figure 3; Table 2; task performance in Table 3). As predicted from gradual-consolidation models, EE participants did not show evidence of lexical integration soon after training (or on Day 2): participants' response times were similar to words that did, and did not, lexically neighbor the learned words (Day 1: $t(24) = 0.36$, $p = 0.72$; Day 2: $t(23) = 0.18$; $p = 0.86$). On the other hand, FM participants showed evidence of lexical integration 10 minutes after training, and again on the following day, with slowed responses to words that lexically neighbor the new words (compared to non-neighbors) on Day 1 ($t(23) = 3.30$, $p = 0.003$) and Day 2 ($t(24) = 3.69$; $p = 0.001$). The FM group's lexical competition was significantly greater than the EE group's on Day 1 ($t(1,47) = 2.43$; $p = 0.02$, $d = 0.69$) and Day 2 ($t(1,47) = 1.98$, $p = 0.05$, $d = 0.56$).

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

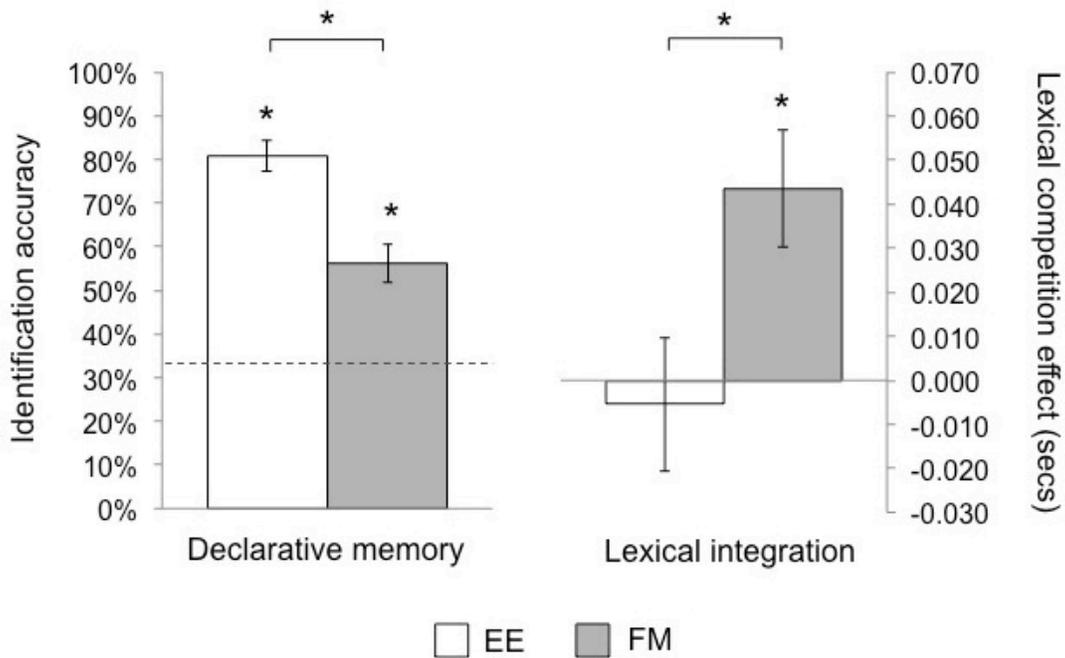


Figure 3: Declarative memory and lexical integration results for Day 1 of Experiment 1. In the declarative recognition memory test (left), participants were presented with a learned word and three learned animals (one correct and two foils). The dashed line reflects chance (33%). The lexical integration test (right) measured lexical competition, by subtracting response times to control words from response times to words that lexically neighbor the learned words. A positive value therefore reflects slowed responses due to lexical competition. Error bars show the standard error of the mean. EE = Explicit Encoding; FM = Fast Mapping. Asterisks indicates statistical significance at $p < 0.05$ compared to baseline or between groups.

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

Condition	Non-hermits	Hermits	Non-hermits – hermits
Experiment 1			
EE (day 1)	0.744 (0.14)	0.750 (0.16)	-0.005 (0.08)
EE (day 2)	0.730 (0.15)	0.727 (0.13)	0.003 (0.08)
FM (day 1)	0.755 (0.12)	0.711 (0.14)	0.043 (0.06)
FM (day 2)	0.721 (0.14)	0.679 (0.12)	0.042 (0.06)
Experiment 2			
EE	0.735 (0.14)	0.740 (0.13)	-0.005 (0.09)
FM	0.724 (0.10)	0.679 (0.11)	0.045 (0.06)
IE	0.722 (0.11)	0.729 (0.12)	-0.007 (0.06)

Table 2: Mean reaction times (seconds) in the lexical competition test by condition. Standard deviations are shown in parentheses. EE = Explicit Encoding; FM = Fast Mapping; IE = Incidental Encoding.

Condition	Overall	Non-hermits	Hermits
Experiment 1			
EE (day 1)	90% (6%)	86% (10%)	94% (7%)
EE (day 2)	91% (7%)	90% (9%)	93% (7%)
FM (day 1)	87% (10%)	88% (8%)	88% (10%)
FM (day 2)	91% (7%)	90% (9%)	92% (9%)
Experiment 2			
EE	89% (8%)	87% (12%)	88% (13%)
FM	90% (4%)	89% (8%)	91% (7%)
IE	90% (7%)	87% (10%)	90% (11%)

Table 3: Mean accuracies in the lexical competition test by condition. Standard deviations are shown in parentheses. EE = Explicit Encoding; FM = Fast Mapping; IE = Incidental Encoding.

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

During the final debriefing, participants were asked to record any words that the animals' names reminded them of. The FM and EE groups did not differ in the number of lexically neighboring hermits they listed ($U = 254$, $p = 0.35$), suggesting the group differences in lexical competition did not depend on conscious awareness of the generating hermits.

As names of animals, the learned words carried semantic meaning. We examined semantic integration after FM and EE by evaluating whether the new words prime related (already-known) concepts. After EE, participants did not show semantic priming on the first ($t(24) = 1.61$, $p = 0.12$; M priming score = -31 ms, s.d. = 95 ms) or second day ($t(24) = 0.12$, $p = 0.91$; M priming score = 2 ms, s.d. = 69 ms; Table 4). Following FM, participants demonstrated priming on the second day ($t(23) = 3.07$, $p = 0.005$; M priming score = 30 ms, s.d. = 48 ms), although this had not yet developed on the day of training ($t(22) = 0.20$, $p = 0.84$; M priming score = 3 ms, s.d. = 70 ms). Task accuracy was near ceiling for both groups (EE day 1: M = 94%, s.d. = 6%; EE day 2: M = 96%, s.d. = 3%; FM day 1: M = 91%, s.d. = 11%; FM day 2: M = 93%, s.d. = 10%). The second day's priming was greater after FM than after EE ($t(1,47) = 1.99$, $p = 0.05$, $d = 0.57$; from comparing 'related' and 'unrelated' response times as a ratio of 'unrelated', to account for individual differences), while the first day's was not ($t(1,46) = 1.58$, $p = 0.12$, $d = 0.46$).

Condition	Related	Unrelated	Unrelated – related / unrelated
EE (day 1)	0.749 (0.149)	0.718 (0.150)	-0.048 (0.119)
EE (day 2)	0.661 (0.119)	0.663 (0.118)	-0.002 (0.087)
FM (day 1)	0.676 (0.134)	0.679 (0.131)	0.0005 (0.089)
FM (day 2)	0.657 (0.152)	0.687 (0.162)	0.041 (0.061)

Table 4: Mean reaction times (seconds) in the semantic priming task by condition. Standard deviations are shown in parentheses. EE = Explicit Encoding; FM = Fast Mapping.

Experiment 2

The results from the second experiment replicated those of the first: Recognition memory was again superior after EE (M = 84.8%, s.d. = 10.3%) compared to FM (M = 49.4%, s.d. = 15.0%; $t(1,38) = 8.69$, $p < 0.001$, $d = 2.75$; Figure 4). The reverse effect for lexical competition

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

was also again observed: FM ($t(19) = 3.43$, $p = 0.003$), but not EE ($t(19) = 0.26$, $p = 0.80$), led to slowed responses to existing words that were lexically similar to the newly learned words (Table 2; task performance in Table 3). This competition was again greater in the FM than EE group ($t(1,38) = 2.04$; $p = 0.048$, $d = 0.65$; Figure 4).

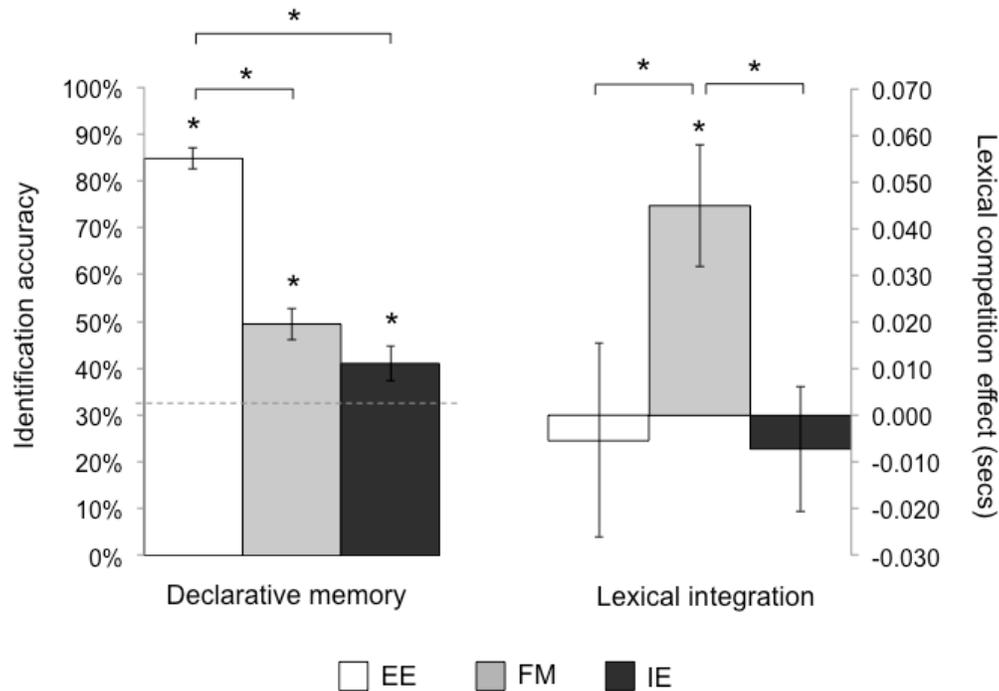


Figure 4: Declarative memory and lexical integration results for Experiment 2. In the declarative recognition memory test (left), participants were presented with a learned word and three learned animals (one correct and two foils). The dashed line reflects chance (33%). The lexical integration test (right) measured lexical competition, by subtracting response times to control words from response times to words that lexically neighbor the learned words. A positive value therefore reflects slowed responses due to lexical competition. Error bars show the standard error of the mean. EE = Explicit Encoding; FM = Fast Mapping; IE = Incidental Encoding. Asterisks indicates statistical significance at $p < 0.05$ compared to baseline or between groups.

In addition to this replication, Experiment 2 introduced a third condition to investigate the basis for the FM-induced rapid lexical integration. This IE condition presented the novel names within the same questions as the FM condition, but without an accompanying known animal on-shown (i.e., only the new animal was shown). In declarative memory, IE participants ($M = 41.0\%$, $s.d. = 16.8\%$) closely resembled the FM group ($t(1,38) = 1.67$, $p = 0.10$, $d = 0.53$; Figure 4), with significantly lower performance than EE participants ($t(1,38) = 9.92$, $p < 0.001$, $d = 3.14$). The IE participants did not show lexical competition however ($t(19) = 0.54$, $p = 0.60$),

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

with significantly less competition than after FM ($t(1,38) = 2.78, p = 0.008, d = 0.88$), and a similar level to EE ($t(1,38) = 0.08, p = 0.94, d = 0.02$; response times in Table 2; task performance in Table 3).

The animal names used in Experiment 2 were counterbalanced, so that pre-existing hermit words generated learned words for some participants, while being a (contrasting) non-neighbor for other subjects. We used the power of this paired design with thirty-two items to also examine lexical response-times, with items as a random effect. This analysis showed that, consistent with the prior results, the words' response times were slower when they were lexical neighbors of the learned names, compared to when they were control hermits (i.e., non-neighbors) following FM ($t(31) = 2.56, p = 0.02$), but not after EE ($t(31) = 0.81, p = 0.42$) or IE ($t(31) = 0.86, p = 0.40$). This lexical-neighbor effect was greater after FM than EE ($t(31) = 2.01, p = 0.05$) and IE ($t(31) = 3.01, p = 0.005$). This item-based analysis supports the conclusion that this effect is not specific to this particular sample of hermit words.

Discussion

We have presented evidence that FM can promote the rapid integration of new words into memory networks. Experiment 1 revealed that while EE gives superior declarative memory of novel animals, subjects do not show lexical integration in the 24 hours after EE training. In contrast, after FM, participants showed evidence of lexical competition ten minutes after training, which continued to the following day. On this second day, words learned through FM (but not EE) could prime related concepts. We replicated the key effects in Experiment 2, and further found that the concurrently shown known animal in the FM procedure is crucial for the effect: without this accompanying item, lexical competition was absent.

The findings presented here are consistent with the idea that learning through FM can lead to a more rapid integration of newly learned words into existing memory networks. But, as learning through FM gives weaker declarative learning, this rapid integration may come at a cost of reduced on-demand memory access. Interestingly, these results parallel dissociations between declarative and non-declarative word learning that have been reported for some patients with hippocampal damage, where individuals do not have conscious access to knowledge they acquire (Bayley & Squire, 2002). On the other hand, successful learning in these patients requires many repetitions, in contrast to the procedures here, where just two trials were presented for each item. The results from the FM and IE conditions also support conclusions by Halberda (2006; from eye-tracking data) that the behavior of linking a novel name to an object during FM encoding is motivated by actively rejecting the known object as a possible referent ('disjunctive syllogism'), rather than by simply linking the word to any novel stimulus ('map-novelty-to-novelty'). Here, when we presented participants with just the novel word and stimulus in the IE condition, we did not see the lexical competition effects that characterized the FM condition. This supports Halberda's (2006) call for relevant cognitive models to incorporate the weighting of negative evidence when identifying the target of a novel label.

Semantic memory theories have hypothesized that neural representations for known items are encoded within distributed and overlapping neural activity of the neocortex (e.g., McClelland, 2011). Specifically, regions of the anterior temporal cortex have been identified as a likely site of this information (McClelland, 2011). Consistent with this, we recently showed that neural signatures in the anterior temporal lobe encode the identity of a retrieved known object, which in turn reflects the integration of featural knowledge held in earlier brain areas (Coutanche

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

& Thompson-Schill, 2014). Notably, theories of semantic memory predict that the neural representations for known concepts overlap with each other to a degree based on their similarities to one another: “the representation of any dog will generally have much more overlap with the representation of a goat, say, than it will with the representation of say, a maple tree” (p. 6-7, McClelland, 2011). The data we present here show that retrieving a known item and engaging in (disjunctive syllogism) inference plays a crucial role in subsequent rapid lexical integration. Combining this result with theories of semantic memory, accessing the memory representation of an existing concept during FM (e.g., retrieving ‘cricket’ in order to answer if the antennae of the ‘torato’ are pointing upward) will be accompanied by increased neural activity for ‘cricket’ and similar known concepts (such as other insects). Indeed, were the torato already known, we could imagine that neurons encoding properties of this concept would likely be activated whenever ‘cricket’ is retrieved. One intriguing possibility is that accessing the neural representation for a known concept during FM enables the new item to “take its place” (albeit at least to a preliminary degree) within the currently active neural network. We can, for now, only speculate about this possibility, however recent findings on the role of schema in learning may shed some light on this putative process. In instances of existing relevant knowledge (where a schema is already in place), learning can be extremely rapid (Tse et al., 2007; Tse et al., 2011; Van Kesteren, Rijpkema, Ruiter, Morris, & Fernández, 2014). Recent neuroimaging findings suggest that the presence of schema can impact the neurobiological systems involved during encoding (Van Kesteren et al., 2014).

McClelland (2013) recently presented model simulations that account for this schema-consistent boost within the CLS framework, suggesting that neocortical learning should be considered ‘prior-knowledge dependent’ rather than ‘slow’. Interestingly, examples of successful semantic learning in amnesic patients are almost all confined to instances where patients already have related prior knowledge (Gordon Hayman et al, 1993; Skotko et al., 2004). Thus, when new information can be ‘anchored’ to existing knowledge, learning can occur even with extensive hippocampus damage. Integrating these results with the neurobiological theories discussed above, it is possible that the presence of a known item (here, animals from the same taxonomic class) can activate a relevant schema (instantiated through activity in relevant distributed neural populations in the temporal cortex), which in turn facilitates the integration of the new item into semantic memory. Indeed, it is noteworthy that recent simulations of learning schema-consistent

knowledge used ‘taxonomic classes’ (and their typical features) as the schema (McClelland, 2013).

While the above discussion highlights the potential for more rapid integration into cortical networks, this does not exclude the possibility of hippocampal involvement in fast mapping for healthy adults. Two recent studies (Smith et al., 2014; Warren & Duff, 2014) failed to find a FM benefit in patients with more extensive hippocampal damage than in Sharon et al. (2011), raising the possibility that the hippocampus may still play some role. Regardless of this debate of hippocampal independence (or lack of), our findings here speak to FM promoting cortical memory integration.

Our findings might also provide a solution to a problem identified in infant learning. Horst and Samuelson (2008) reported that 2-year old infants failed at (declarative) retention after a short delay (although see Spiegel & Halberda, 2011 for an example of successful retention), leading to the question of how an initially fast mapped word is later consolidated to make it consciously accessible (i.e., What is needed to bridge fast and slow mapping? See Kucker and Samuelson, 2012 [p. 297] for a relevant discussion). The lexical integration we observed here (after just two presentations) may provide important ‘support’ for subsequent gradual consolidation, possibly in conjunction with further repetitions (Kucker and Samuelson, 2012).

Like the EE and IE conditions in this study, most investigations find that lexical integration does not occur immediately after (non-FM) training. Some studies have found evidence for integration on the day following training (e.g., Bowers et al., 2005), although its absence here in the EE condition is consistent with a recent finding that adding an image to (non-FM) word learning delays lexicalization until after Day 2 (Takashima, Bakker, van Hell, Janzen, & McQueen, 2014). Our findings of earlier integration after FM (in which two images are presented) are thus all the more striking. The precise timing of EE integration may also be affected by giving our words meaning (i.e., animal names), in contrast to other studies (e.g., Bowers et al., 2005).

In this work, we also report accelerated semantic priming after FM. This is an intriguing result, although we consider it preliminary, since the design of Experiment 1 does not allow us to distinguish between the FM-acceleration requiring less time or fewer repetitions. Specifically, although the importance of time (and sleep) for semantic effects has been documented (e.g., semantic effects can take up to a week to emerge; Clay et al., 2007; Tamminen & Gaskell, 2013),

FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

here the semantic-integration test followed the forced-choice recognition test, in which the new words were presented several times. Thus, we cannot exclude the possibility that FM might lead to semantic integration following fewer repetitions than EE. These interesting alternatives warrant clarification in future work. Similarly, future studies may wish to delineate the precise roles of features of the FM paradigm, such as the emphasis placed on semantic information by the question and second image.

The results we report have revealed a behavioral signature of FM: rapid lexical integration. We discovered this signature by examining multiple behavioral markers of memory change (declarative, lexical and semantic integration tests) in the same study. This approach of probing learned associations through multiple avenues is an effective approach to characterizing underlying learning (also see Coutanche & Thompson-Schill, 2012), which may help further elucidate FM in the future. The importance of employing suitable learning measures has recently been highlighted in the developmental literature, where there is a “need to find more sensitive measures of learning” (p. 139, Spiegel & Halberda, 2011). The dissociation we report suggests that assessing lexical integration could be one such measure.

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FAST MAPPING RAPIDLY INTEGRATES NEW INFORMATION

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