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Learning from input and memory evolution: Points of vulnerability on a pathway to mastery in word learning

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Abstract

Word learning consists of at least two neurocognitive processes: learning from input during training and memory evolution during gaps between training sessions. Fine-grained analysis of word learning by normal adults provides evidence that learning from input is swift and stable, whereas memory evolution is a point of potential vulnerability on the pathway to mastery. Moreover, success during learning from input is linked to positive outcomes from memory evolution. These two neurocognitive processes can be overlaid on to components of clinical treatment with within-session variables (i.e., dose form and dose) potentially linked to learning from input and between-session variables (i.e., dose frequency) linked to memory evolution. Collecting data at the beginning and end of a treatment session can be used to identify the point of vulnerability in word learning for a given client and the appropriate treatment component can then be adjusted to improve the client's word learning. Two clinical cases are provided to illustrate this approach.

Keywords

vocabulary; word learning; input; memory evolution; clinical treatment

Typically developing children and adults have an amazing ability to learn new words. Estimates of the number of words learned per day vary, but seem to converge around 7 words per day (cf., Beck, McKeown, & Kucan, 2002). Likewise, numerous studies suggest that children and adults can extract initial information about a word after a single exposure, although much greater exposure is needed to accrue a rich and detailed representation that includes information such as word form, semantics, morphology, and syntax (e.g., Carey, 1978, 2010; Carey & Bartlett, 1978). Although robust word learning is frequently touted as almost a hallmark of typical language development, in reality there is tremendous variability. Among children and adults recruited from relatively similar environments, variation between participants during experimental studies of word learning shows a moderate effect on learning (Storkel, Bontempo, Aschenbrenner, Maekawa, & Lee, 2013; Storkel, Bontempo, & Pak, 2014). This variation is exacerbated when participant characteristics are manipulated. For example, children from higher socioeconomic groups appear to know (at least) twice as many words as children from lower socioeconomic

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groups, and this discrepancy is relatively stable (or even worsening) over time (e.g., Graves, Brunetti, & Slater, 1982; Hart & Risley, 1995). Likewise, if individuals with communication disorders are included, the difference in word learning is even more marked. For instance, children with Specific Language Impairment (SLI) struggle to learn new words, needing two to three times as many exposures as their typically developing peers to learn a new word (Gray, 2003; Rice, Oetting, Marquis, Bode, & Pae, 1994).

Variation in word learning has significant consequences. Vocabulary is often taken as an index of overall language skills. Thus, a person with less well developed vocabulary may not be perceived as a gifted or even competent communicator. Moreover, vocabulary is often measured on tests that serve as a gateway to educational opportunities (e.g., Graduate Record Examination, which is used in the USA for entry into university graduate programs). Poor scores on these vocabulary measures may limit educational opportunities and, in turn, employment prospects. In addition, word learning in spoken language has implications for written language. The emergence of phonological awareness, an important pre-reading skill, has been linked to vocabulary (Metsala & Walley, 1998; Walley, Metsala, & Garlock, 2003). In addition to assisting children in learning to read, early vocabulary is a predictor of later reading comprehension (Cunningham & Stanovich, 1997; Scarborough, 1998). Finally, current vocabulary impacts current reading comprehension (Ouellette, 2006). In particular, it is difficult to understand what you read if you do not know the words.

Taken together, variation in word learning is rampant, with significant consequences for communication, educational achievement, and employment opportunities. As a result, it is crucial to understand how words are learned so that early identification can be improved and so that clinical and educational practices in teaching words can be enhanced to minimize or eliminate poor outcomes. This goal is facilitated by considering what is already known about learning and memory, in general, and applying this knowledge to word learning. In particular, there is evidence that learning and memory involves at least two neurocognitive processes: (1) learning from input; (2) memory evolution in the absence of input (Davis, Di Betta, Macdonald, & Gaskell, 2009; Davis & Gaskell, 2009; Henderson, Weighall, & Gaskell, 2013; McClelland, McNaughton, & O'Reilly, 1995; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2000).

Data from Storkel and colleagues (2014) will be used to describe and illustrate these two neurocognitive processes. In this study, 61 adults were taught two sets of novel words paired with novel objects. This illustration will focus on the first set of 12 words taught but will aggregate across a stimulus manipulation (i.e., low versus high phonological neighborhood density, defined as the number of words that differ by a single sound from the target word). The procedure entailed repeated cycles of training and testing. During the training phase, adults received five auditory exposures to each novel word while viewing a picture of the novel object on a computer screen. During the testing phase, adults were shown each novel object picture and asked to name the object using the trained novel word. Responses were scored as correct if all three target phonemes were produced correctly in the appropriate order. Although word learning entails learning multiple pieces of linguistic information (e.g., word form, semantics, morphology, syntax), the picture naming task predominately taps learning of the word form. On the first day of training, three cycles were completed, yielding 15 total exposures and three separate test points. These test points tapped learning from input. Approximately one week later, adults returned and completed the naming test again. This test point tapped memory evolution in the absence of input. Then, an additional three cycles were completed, yielding an additional 15 exposures to the novel words and three additional test points tapping learning from input. Approximately one week later, adults returned and completed a final naming test, providing a second window into memory evolution in the absence of input. Figure 1 shows the percent of correct responses on the naming test at each of the eight test points.

Learning from input

The shaded bars in Figure 1 highlight the six naming tests that occurred during training. These tests tap learning from input. That is, the adult has just received five exposures to each of the 12 novel words and then is immediately tested on those same 12 words via picture naming. Thus, this test captures information about the new memory that was created (or updated) from the input provided. This has been referred to elsewhere as encoding (McGregor, 2014; McGregor et al., 2013) or configuration (Leach & Samuel, 2007). For the data illustrated in Figure 1, successful naming of the picture presumably indicates that an accurate representation of the word form, at least an initial or partial representation of the novel object referent, and an association between these two representations has been stored in memory. As shown in Figure 1, learning from input is swift (cf., Davis et al., 2009; Davis & Gaskell, 2009; Henderson et al., 2013; McClelland et al., 1995; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2000), especially during the first day of training where accuracy increases by approximately 30% with the first five exposures (i.e., Day 1: Test 1) and by another 30% with the second five exposures (i.e., Day 1: Test 2). Gains then begin to level off as ceiling performance is approached.

During this training-testing period, learning from input is argued to be episodic, meaning that the new memory is affiliated with the details of the learning experience (Davis et al., 2009; Davis & Gaskell, 2009; Henderson et al., 2013; McClelland et al., 1995; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2000). That is, one could think of the novel word as having an exemplar representation in memory, meaning that the representation would contain critical details as well as ancillary details (e.g., details of the speaker’s voice). Hardt, Nader, and Nadel (2013) refer to this as “promiscuous encoding” (p. 112) to indicate that a great deal of information is preserved in this initial representation that is formed during input. Lastly, it is argued that the hippocampus plays a crucial role during learning from input, allowing for the details of the experience to be stored and bound together (Davis et al., 2009; Davis & Gaskell, 2009; Henderson et al., 2013; McClelland et al., 1995; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2000). Thus, the initial representation of the word is thought to be stored in the hippocampus rather than the cortex.

Memory evolution

The open bars in Figure 1 highlight the two naming tests that occurred after an approximately 1-week gap in training. These tests tap memory evolution in the absence of input. Here, training has ended but memory for the input continues to change during the 1-

week interval without training. The question then becomes what happens to that initial representation that was formed during input? Recall that correct naming was thought to indicate that an accurate representation of the word form, at least an initial or partial representation of the novel object referent, and an association between these two representations had been stored in memory. Will those initial representations be retained after training is withdrawn?

Within current memory models, changes in the absence of input are thought to occur over longer timescales, making memory evolution a slower process than learning from input (Davis et al., 2009; Davis & Gaskell, 2009; Henderson et al., 2013; McClelland et al., 1995; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2000). It is assumed that memory evolution involves a transference from the hippocampal system to the relevant cortical system based on the type of memory (Davis et al., 2009; Davis & Gaskell, 2009; Henderson et al., 2013; McClelland et al., 1995; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2000). For words, the initial representation would be transferred to the areas of the cortex that make up the language system. In addition, memory evolution is hypothesized to be dependent on sleep and, more specifically, the neural events that occur during sleep (Davis et al., 2009; Davis & Gaskell, 2009; Henderson et al., 2013; McClelland et al., 1995; Norman & O'Reilly, 2003; O'Reilly & Rudy, 2000).

The term memory evolution is used because there are several possible events that could occur when the memory is transferred to the cortex (Walker & Stickgold, 2010). Memories may be consolidated, meaning that the memories are retained, stabilized, and strengthened by being incorporated into the appropriate cortical system (Stickgold & Walker, 2013; Walker & Stickgold, 2010). This also entails new memories being integrated with old memories so that new and old memories can influence one another (Davis et al., 2009; Davis & Gaskell, 2009; Stickgold & Walker, 2013; Walker & Stickgold, 2010). For example, the initial representation of the word form would be linked to existing representations of similar known word forms. In this way, the new word is incorporated into an existing phonological neighborhood, which could further reinforce and strengthen the representation of the new word form (Storkel & Lee, 2011). A similar process presumably occurs for other linguistic information (e.g., semantics). This integration of old and new memories can facilitate new behavior, namely generalization to new instances (Stickgold & Walker, 2013; Walker & Stickgold, 2010). For example, although only one picture of the novel object may have been shown during training, integration with similar objects (e.g., other toys) may reinforce crucial properties of the object (e.g., shape). This, in turn, may facilitate recognition that a different picture of the novel object that varies in color and size but shares shape with the original object should still be called by the same name. On this side of memory evolution, the outcome is positive with the new memory being retained across the gap in training and, in some cases, performance may even appear to improve across the gap (cf., Gaskell & Dumay, 2003; Rice et al., 1994; Storkel, 2001, 2003; Storkel & Lee, 2011).

On the other hand, the open bars in Figure 1 show a negative outcome across the gap in training. Here, there is clear evidence of forgetting. Performance is much worse after the gap in training, with accuracy returning to a level similar to the beginning of training (e.g., compare Day 2: Test 4 to Day 1: Test 1). Thus, some of the new representations that were created during training were not retained when training was withdrawn. This forgetting of newly learned words is not specific to our study (cf., Storkel et al., 2013; Tamminen & Gaskell, 2013; Vlach & Sandhofer, 2012). In general, forgetting is thought to occur through a variety of mechanisms. One possibility is that the new memory may simply decay in the hippocampal system as time passes and the individual remains awake, delaying the transfer of the new memory to the cortical system, which is thought to require sleep (Hardt et al., 2013). This hypothesis is supported by various studies demonstrating the benefit of sleep on learning (Backhaus, Hoeckesfeld, Born, Hohagen, & Junghanns, 2008; Brown, Weighall, Henderson, & Gareth Gaskell, 2012; Dumay & Gaskell, 2007; Gomez, Bootzin, & Nadel, 2006; Henderson, Weighall, Brown, & Gareth Gaskell, 2012; Hupbach, Gomez, Bootzin, & Nadel, 2009; McGregor, 2014; Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010). A related hypothesis is that forgetting occurs due to interference between the new memory in the hippocampal system and ongoing activities, such as encoding new information, while awake (Wixted, 2004). In both of these cases, forgetting is hypothesized to occur in the hippocampal system due to a delay in transferring the memory from the hippocampal to the cortical system during time spent awake rather than asleep. Applying either of these possibilities to the current word learning data, the accurate representation of the word form, the initial or partial representation of the novel object referent, and the association between these two representations would decay or degrade during the gap in time between training and sleep. Thus, a less accurate or detailed representation is transferred to the cortical system.

Another possibility is that forgetting occurs due to interference or competition between the new memory and old memories in the cortical system (Hardt et al., 2013). Here, integrating the new memory with old memories does not have a positive outcome (i.e., strengthening the new memory) but rather may degrade the new memory. As an illustration of this scenario for word learning, the accurate representation of the word form (for example) is transferred to the cortical system but when this accurate representation links to similar word forms, competition or interference arises, degrading the representation of the new word form. A final possibility is that all of these mechanisms may be in play and may contribute to forgetting. It should be noted that not all forgetting is negative. At least some of the information that is initially encoded is irrelevant (Hardt et al., 2013). Loss of irrelevant details could have positive effects, such as promoting generalization (Stickgold & Walker, 2013; Vlach, 2014; Vlach & Sandhofer, 2012). For example, although the training input may have been in the voice of one speaker, loss of detailed characteristics of the voice of that speaker might facilitate recognition of the new word when produced by a different speaker with a different voice, dialect, or accent.

Taken together, data and theory suggest that a key limiting factor in word learning may be memory evolution. In general, experimental studies of word learning almost universally show strong learning from input. As noted previously, memory evolution appears to vary across studies with some studies showing positive retention and even continued improvement in the absence of input (e.g., Gaskell & Dumay, 2003; Rice et al., 1994; Storkel, 2001, 2003; Storkel & Lee, 2011) but others showing massive forgetting when the training input is withdrawn (e.g., Storkel et al., 2013; Storkel et al., 2014; Tamminen & Gaskell, 2013; Vlach & Sandhofer, 2012). The difference across studies that might trigger these outcomes is not obvious but this variability warrants better understanding because the outcome of memory evolution has major consequences for word learning success. As shown in Figure 1, forgetting lead to appreciable decrements in performance, slowing mastery of the new words. To attempt to understand the interplay between learning from input and memory evolution, a fine-grained analysis of the data from Storkel and colleagues (2014) was undertaken.

Fine-grained analysis of Storkel et al. (2014)

To provide greater insight into the unfolding of learning from input and memory evolution, the pattern of correct and incorrect responses was examined across each test point. Although this approach has been used in prior studies (Fenn & Hambrick, 2013; Gershkoff Stowe & Hahn, 2013; Senechal & Cornell, 1993), the current data set is unique in the large number of test points used to capture learning over multiple training cycles and two retention tests. The full data set was used without aggregating across novel words or participants, yielding 732 observations (i.e., 61 participants × 12 novel words). Each observation consisted of the pattern of correct and incorrect responses across the eight test points. For example, if a novel word was responded to correctly by a particular participant at all eight test points, the observation would consist of a series of eight correct responses (i.e., 1-1-1-1-1-1-1-1). This was the most frequent pattern, occurring in 17% of the observations. As shown in the appendix, 86 different patterns of correct and incorrect responses across the eight test points were observed. Note that the possible number of different combinations of correct and incorrect responses across the eight test points is 256 (i.e., 2^8). Thus, only 34% of possible patterns were observed. By examining the patterns that did occur, useful information about the pathways that different words take to mastery may be gleaned. To illustrate common patterns, a flowchart was created to track correct and incorrect responses across the test points (Figures 2-4).

Day 1 learning from input and Day 2 memory evolution

Figure 2 shows the flowchart for the first day of training and the first retention test. To conserve space, response categories representing 2% or less of the observations are not included in Figure 2. However, the total data represented in Figure 2 is noted to clarify when data are dropped from the figure. Generally, during training, when a novel word is responded to correctly at one test point, it tends to be responded to correctly at the remaining test points during training, indicating that the word is maintained during training. For example, 31% of the novel words were responded to correctly at Day 1: Test 1. Following this 31% to Day 1: Test 2, 28% were responded to correctly again (i.e., maintained) whereas 3% were responded to incorrectly (i.e., lost). Continuing to follow these items to Day 1: Test 3, 27% were responded to correctly again (i.e., still maintained). Thus, in this pathway, correct items tended to stay correct throughout training. Turning to the second pathway on Day 1: Test 1, 69% of items were responded to incorrectly at Day 1: Test 1 (i.e., not learned). Following these items, 32% are responded to correctly at Day 1: Test 2 (i.e., newly learned). Following this 32% to Day 1, Test 3, 29% were responded to correctly again (i.e., maintained) whereas 3% were responded to incorrectly (i.e., lost). Again, correct items tended to stay correct throughout training. These two pathways indicate that once an item is responded to correctly during training, it tends to continue to be responded correctly throughout training (i.e., Day 1).

Figure 2 also illustrates the slight deceleration in learning during the first day of training. As already noted, approximately 31% of items are responded to correctly for the first time at Day 1: Test 1. At Day 1: Test 2, an additional 32% of items are responded to correctly for the first time. In contrast, at Day 1: Test 3, only 14% of items are responded to correctly for the first time (i.e., newly learned). Notably, 23% of items at Day 1: Test 3 have never been responded to correctly during training. The reason for these diminishing returns during the third training cycle is unclear. Perhaps adults are beginning to fatigue by the third training cycle and do not learn as much due to that fatigue. Alternatively, the items that have not yet been learned may be more difficult to learn or the training may be less effective for these items. Lastly, both issues could be contributing to the deceleration in learning at the last training cycle. Further investigation is warranted to better understand the factors that contribute to robust learning during input.

Turning to memory evolution, performance on Day 2: Test 4 appears to be influenced by the pattern of correct responses during training. For the top pathway in Figure 2, the novel words were responded to correctly at all three test points during Day 1 training. At the retention test 1-week later, 18% are responded to correctly, indicating that these words were retained, whereas 9% are responded to incorrectly, indicating that these words were forgotten. This represents a 2-to-1 ratio of retention to forgetting, indicating that retention is more likely for these items. In contrast, in the second pathway in Figure 2, the novel words were responded to correctly at the latter two test points during Day 1 training. At the retention test, 13% are responded to correctly (i.e., retained) whereas 16% are responded to incorrectly (i.e., forgotten). This represents a 1-to-1.2 ratio of retention to forgetting, indicating that retention and forgetting are relatively equally likely. Moving to the third pathway in Figure 2, these novel words were responded to correctly only at the last test point during Day 1 training. At the retention test, only 3% are responded to correctly (i.e., retained) whereas 11% are responded to incorrectly (i.e., forgotten). This represents a 1-to-3.7 ratio of retention to forgetting, indicating that forgetting is more likely for these items.

Taken together, the number of correct responses during training appears to be linked to the likelihood of retention or forgetting when training is withdrawn. This suggests that the stability or strength of the memory during learning from input is linked to the outcome of memory evolution. Those memories that display more stable or stronger memory traces during learning, as indexed by more correct responses, seem more likely to be further strengthened or stabilized by memory evolution. In contrast, memories that appear more vulnerable during learning, as indexed by fewer correct responses, seem less likely to be strengthened or stabilized by memory evolution. A related point in terms of the mechanism for this strengthening is that an emerging representation, as indexed by a correct response, is further reinforced by the ongoing training, strengthening or stabilizing the representation. That is, when there is evidence of an emerging representation at the first test point (i.e., a correct response), that representation is reinforced during the remaining two training cycles; whereas when the emerging representation appears at the second test point, there is only one additional training cycle to reinforce the representation. Lastly, if the emerging representation appears at the third test point, there are no additional training cycles so there is no further reinforcement to the new representation. In this way, performance during learning from input may be predictive of memory evolution.

Day 2 learning from input and Day 3 memory evolution

What happens to these items when training is re-instated on Day 2 and memory evolution is re-tested on Day 3? To address this issue, the items that showed some evidence of learning during Day 1 (70% of items) are considered separately in Figure 3 from those that showed no evidence of learning on Day 1 or at the Day 2 retention test (21% of items), which are shown in Figure 4. Focusing first on the novel words that showed evidence of learning on Day 1 (i.e., Figure 3), it appears that the number of correct responses on the first day of training had minimal, if any, influence on future training and retention. Figure 3 repeats the results for Day 2: Test 4. The items that were retained across this first gap in training (open boxes in Figure 3), tended to be answered correctly at all tests during Day 2 training and at the Day 3 retention test. This suggests that these novel words were essentially mastered when they were responded to correctly at the first retention test (Day 2: Test 4) because they were rarely responded to incorrectly after that point. This pattern is similar across the different paths in Figure 3, which correspond to the number of correct responses during training on Day 1.

Turning now to the items that were forgotten at Day 2: Test 4 (shaded boxes in Figure 3), these novel words showed strong and robust re-learning when training was re-introduced on Day 2. After the first cycle of 5 exposures (Day 2: Test 5), almost all of the items were responded to correctly. In addition, these re-learned items were responded to correctly at the remaining two test points during Day 2 training. Lastly, they also were responded to correctly following the second gap in training (Day 3: Test 8). Thus, these items appeared to be mastered at Day 2: Test 5 with the addition of just one more training cycle due to strong re-learning of the novel words. Once again, this pattern is similar across the different paths in Figure 3, which correspond to the number of correct responses during training on Day 1.

As shown in Figure 4, novel words that were not responded to correctly during Day 1 training or at the Day 2 retention showed learning patterns that resembled those observed during Day 1 training. For example, 7% of these novel words were responded to correctly at Day 2: Test 5 and continued to be responded to correctly at the two subsequent test points (Tests 6 and 7). Following the gap in training, these items showed a retention-to-forgetting ratio of 1.5 (3%) to 1 (2%), indicating that retention is slightly more likely for these novel words. For items that were incorrect at Day 2: Test 5, 3% of these were responded to correctly at Day 2: Test 6 and continued to be responded to correctly at the last test point (Test 7). Following the gap in training, these items showed a 1-to-2 ratio of retention to forgetting, indicating that forgetting was slightly more likely. Lastly, there were a small number of items (2%) that were responded to correctly for the first time at the last test point during training (Day 2: Test 7) and these items were more likely to be forgotten. Rounding in Figure 4 somewhat obscures these results. With more decimal places, only 0.27% of items were retained whereas 1.37% of items were forgotten, leading to a 1-to-5 ratio of retention-to-forgetting. Overall, there were parallels to the first day of training. Specifically, once an item was responded to correctly during Day 2 training, it tended to be responded to correctly for the remainder of the Day 2 tests. In addition, the number of correct responses during training appeared to be linked to the likelihood of remembering or forgetting the new word after training was withdrawn. Even though these novel words may have, in some way, been more difficult based on the fact that they were not learned during Day 1 training, they still appear to follow similar learning paths when additional training is provided.

Summary of fine-grained analysis

Figure 5 provides a condensed summary of the main pathways identified in the fine-grained analysis. The fine-grained analysis revealed several interesting patterns. First, when adults respond to a novel word correctly during training, they tend to continue to respond to that item correctly throughout that training session. This suggests that learning from input is not only swift but also relatively stable with correct items remaining correct, rather than being unstable with items vacillating between correct and incorrect responses. In this way, a correct response is relatively predictive of a future correct response during training. Second, the number of correct responses during training was linked to retention. That is, when adults responded to a novel word correctly three times during training, they were more likely to retain the word across a gap in training. In contrast, when adults responded to a novel word correctly two times during training, they were equally likely to retain the word or to forget the word across a gap in training. Lastly, when adults responded to a novel word correctly only once during training, they were more likely to forget the word across a gap in training. This pattern indicates that the strength or stability of the memory during learning from input has consequences for memory evolution. A more robust memory is more likely to resist decay or interference during memory evolution so that memory evolution actually strengthens and stabilizes the new memory. In this way, success during learning from input is predictive of success in memory evolution. This finding also highlights memory evolution as a vulnerable point in a pathway to mastering a new word. During training, correct items remain correct. When training is withdrawn, previously correct items can become incorrect. This pattern is illustrated in the top pathway of Figure 5. Third, novel words that are retained across a gap in training were responded to correctly at all remaining test points, as shown in the top pathway of Figure 5. This indicates that mastery of a word entails both correct responses during learning from input as well as correct responses after memory evolution. In addition, this pattern also provides further support for the stability of memory for new words by adults. That is, once a word is recalled across a gap in training, it is not suddenly lost from memory at a later point, although only a relatively short time period was monitored here and the same information was provided at each training. It is possible that a memory for a new word could become unstable as new or conflicting information is encountered about the new word (Hupbach, Gomez, Hardt, & Nadel, 2007; Hupbach, Gomez, & Nadel, 2009, 2013; Nadel, Hupbach, Gomez, & Newman-Smith, 2012). Fourth, novel words that are learned during training but forgotten are quickly re-learned when training is re-introduced, as noted in the second pathway in Figure 5. This indicates that forgetting does not necessarily entail a loss or erasing of the memory. A more likely scenario is that the memory is present but degraded and weak, making the memory insufficient to support correct responding. However, additional training immediately strengthens the memory to support correct responding. A final insight is that more difficult items appear to follow the same pathway as less difficult items. This is illustrated in the third pathway in Figure 5.

Clinical application

It is important to keep in mind that the data from Storkel and colleagues (2014) are from adult college students with a normal developmental and educational history. There are key differences between adults and children that could impact how learning unfolds over time. In particular, adults have greater language experience which could affect learning from input in terms of the ability to rapidly process language, hold novel items in working memory, and create accurate and detailed initial representations in memory. In this same way, adults have a larger language network in which to incorporate a new representation. That is, a representation of a new word would form links with many more existing representations during memory evolution by an adult than by a child. This could impact the amount of benefit or detriment that accrues during memory evolution. Likewise, children or adults with different communication disorders may show problems in learning from input, memory evolution, or both depending on the nature of the deficit. It may be useful to study this unfolding of word learning in these other populations because there is a clear potential relationship between the neurocognitive processes that contribute to word learning and clinical treatment (Baker, 2012; Warren, Fey, & Yoder, 2007).

Specifically, learning from input would occur during treatment with treatment encompassing direct intervention by a clinician as well as related activities (e.g., home practice), although the focus here will be on direct intervention for simplicity of illustration. The main hypothesis is that manipulation of components of a treatment session could potentially influence learning from input. Two components of treatment are dose form and dose (Warren et al., 2007). *Dose form* refers to a teaching episode during treatment where the active ingredient of the treatment is administered. For word learning, this would likely entail the presentation of the word form along with information about the meaning (e.g., picture of the object that the word form refers to, a context sentence where the meaning can be inferred, an explicit definition of the word). Aspects of the word form also could be explicitly highlighted (e.g., dividing the word form into syllables, highlighting the first sound or syllable in the word). In Storkel and colleagues (2014), the dose form was auditory presentation of a novel word in a standard carrier sentence (e.g., “This is a ____”) along with presentation of a black and white novel object (i.e., the referent of the word) on a computer screen. *Dose* is the number of appropriate teaching episodes that occur during a session. For word learning, dose relates to the number of exposures to the words being taught. In Storkel and colleagues (2014), each training cycle included five presentations of the novel word and novel object and there were three training cycles per session, yielding a cumulative dose of 15 exposures to the word form paired with the novel object.

To improve learning from input in Storkel and colleagues (2014), the treatment form could have been enhanced by providing a richer teaching episode or the dose could have been increased. In terms of the treatment form, the exposure to the novel words was not rich, essentially being a simple pairing of novel word and novel object with minimal teaching. Thus, there is room to improve the richness of the treatment form. For example, activities could have emphasized aspects of the novel word, such as explicitly highlighting the first sound (e.g., ____ starts with ____) or the rhyme (e.g., ____ rhymes with ____) or having the participant repeat the novel word (e.g., Say ____). Likewise, activities could have emphasized the meaning of the novel word by highlighting properties of the novel object (e.g., ____ has a ____ shape) or semantic features (e.g., a ____ is a type of ____; a ____ can be used for ____). In terms of dose, a fourth (or more) training cycle could have been added to increase the dose to 20 (or more) exposures.

In contrast, memory evolution relates to the gaps between treatment sessions, which relates to dose frequency (Warren et al., 2007). *Dose frequency* refers to the number of treatment sessions per day or per week. Thus, dose frequency relates to the length of the gap between training sessions as well as the total number of training sessions. In Storkel and colleagues (2014), sessions occurred weekly so the dose frequency was one session per week and the total number of training sessions was two (i.e., Day 1 and Day 2). To enhance memory evolution in Storkel and colleagues (2014), the dose frequency could have been increased to two sessions per week or one session per day. This would minimize the gap between training sessions. Forgetting in word learning appears to follow a curvilinear pattern in both children and adults (Vlach & Sandhofer, 2012). In particular, steep decreases in performance, namely rapid forgetting, are observed between immediate testing and a 1-week retention test but then forgetting levels off after the 1-week retention test, with performance stabilizing at a relatively poor level (Vlach & Sandhofer, 2012). In other words, most of forgetting occurs during the first week after training. Providing an additional one or more training sessions during that 1-week period of rapid forgetting likely would have reduced forgetting. Likewise, more training sessions could have been added, which would support relearning after forgetting had occurred. Lastly, the relationship between performance during training and later retention further suggests that enhancing training by changing the dose form or the dose frequency could also have a positive impact on memory evolution (cf., Vlach & Sandhofer, 2012).

What this means for clinicians is that measuring what a client has learned by the end of a treatment session as well as what a client has retained across the gap between treatment sessions may help pinpoint which neurocognitive process is limiting the client's progress towards mastery. This entails data collection at the beginning and end of each treatment session. Within a session, the gain from the beginning to the end of the session taps learning from input. If gains seem to be small, then the clinician could consider changing the treatment form or the dose and monitor within session gains to determine if the chosen manipulation(s) was effective. Between sessions, the gain or loss from the end of the prior session to the beginning of the new session taps memory evolution. If losses seem to be large, then the clinician could consider increasing the dose frequency to minimize time between treatment sessions and monitor between session gains/losses to determine if the manipulation was effective. In that same vein, the clinician could consider how to involve others (e.g., teachers, parents, the client) in slowing forgetting between treatment sessions through home practice or in-class activities. Likewise, the clinician could also consider changes in treatment form or dose within the session to potentially strengthen or stabilize new memories to enhance memory evolution across gaps in treatment.

Clinical illustration

One difficulty for clinicians is having appropriate treatment gains in mind. That is, the prior discussion referenced somewhat vague concepts of “small gains” or “large losses,” which is clearly open to a clinician’s interpretation of what type of gain is actually possible for a child or an adult with a communication disorder. Clinical expectations can be informed by the research literature, particularly single-subject studies and group studies that provide session-by-session treatment data. In that vein, the following illustration of stronger versus weaker learning during word learning treatment is offered.

Two cases are drawn from a larger on-going preliminary clinical trial of word learning by Kindergarten children with Specific Language Impairment (SLI). The overall purpose of the ongoing study is to determine a promising intensity of an interactive book reading treatment for children with SLI. The two illustrative cases are drawn from the 36 exposures intensity condition. In this intensity, children received six exposures (dose 6) to the selected treated words in a given book reading session. The treatment form included pairing the target word with semantic information supported by pictures and verbal description during (1) preview; (2) book reading; (3) review. During the preview in the 36 exposure condition, children saw a picture depicting the target word and heard the word in two sentences: one introducing a synonym (e.g., “*Marsh* is like a swamp”) and one introducing the definition (e.g., “*Marsh* means a low, wet land, often thick with tall grasses.”). After all six target words for a given storybook were previewed, book reading was initiated. During book reading, children saw the storybook and were read the sentence in the storybook that contained the target word (e.g., “They came down to a *marsh* where they saw a muskrat spring-cleaning his house.”). Then, the experimenter broke from the text and reminded the child of the synonym (e.g., “*Marsh* is like a swamp”). When the end of the book was reached, the review was initiated. Here, the child saw a new picture depicting the target word and heard a context sentence consistent with the picture (e.g., “Ducks and beavers live in a *marsh* because they like water.”). They then were reminded of the definition of the word (e.g., “*Marsh* means a low, wet land, often thick with tall grasses.”).

Children repeated these activities six times for each book (dose frequency 6), yielding a total of 36 exposures to the treated words (i.e., dose 6 × dose frequency 6 = 36 cumulative exposures). In total, five storybooks were used in treatment and each storybook contained six target words (see Justice, Meier, & Walpole, 2005 for a complete list of books and target words). Thus, 30 new words were taught over the course of treatment. In complement, an additional 30 words were not taught during the course of treatment, and these words served as the control words. The control words were selected in the same manner as the treated words. In addition, word sets were randomized to treatment or control across children.

Learning of treated and control words was measured in a picture naming task that was administered at the end of a treatment session periodically. For intensity 36, learning was measured following 6, 12, 24, and 36 exposures. Children were shown one of the pictures from the training and given a leading question prompt (e.g., “what’s this?,” “what is she doing?,” “how does she look?”). A response was scored as correct if it matched the child’s pre-treatment repetition of the same word. Note that this procedure is not well suited to differentiating learning from input versus memory evolution which requires testing at the beginning and the end of treatment sessions, as previously described. However, the data are still useful in illustrating different patterns of learning.

Figure 6 shows the naming data from the two children with SLI who have completed the intensity 36 treatment. One child, KAW015, showed robust learning, acquiring 15 of the 30 treated words; whereas the other child, KAW022, showed more limited learning, acquiring only 8 of the 30 treated words. The graph of KAW015 shows solid word learning performance. Each session appears to build on the prior one with the number of words correct systematically increasing. The more detailed table of the response pattern to individual words yields similar insights. Specifically, 3-7 words were responded to correctly for the first time at each of the four test points, indicating robust learning from input. In addition, words that had previously been responded to correctly were typically responded to correctly at following test points as shown by the shaded areas of the table in Figure 6. Thus, memory evolution also appears strong for this child with the number of words retained from one test point to another increasing across treatment. In total, KAW015 provided at least one correct response to 18 different words with 11 of 18 showing multiple correct responses across test points; 4 of the 18 being correct only at the last test point and thus potential long-term retention is unknown; 3 of the 18 showing a pattern of a correct response at one test point and then incorrect responses at all remaining test points (see silky, prodded, scarlet).

In contrast, the graph for KAW022 shows more modest learning. Sessions appear to build more slowly on one another with small gains between 6 and 12 exposures (i.e., gain of 2) and 12 and 24 exposures (i.e., gain of 3). In addition, there appears to be a plateau between 24 and 36 exposures. The more detailed table of the pattern of responding for treated words that were correct at one test point provides additional insights. In particular, KAW022 responded correctly at least once to 15 different words, which is relatively comparable to KAW015’s 18 different words responded to correctly at least once. In addition, KAW022 showed similarly robust learning from input with 3-5 words responded to correctly for the first time at each of the four test points. The difference between the two children emerges when retention is considered. KAW022 shows minimal increases across test points in the number of words retained, which is in sharp contrast to KAW015. Likewise, KAW022 has a much higher number (and proportion) of words that are correct at one test point and then incorrect at all remaining test points. Specifically, KAW022 shows a correct response at one test point and then incorrect responses at all remaining test points for 6 of 15 (50%) words (see flashing, gathered, awful, gulp, heaved, swaying). This is in sharp contrast to KAW015 who demonstrates this pattern for only 3 of 18 (17%) words.

Notably, the observations from these two cases are consistent with findings from adults with language impairments (McGregor et al., 2013). Specifically, McGregor and colleagues showed variability across adults with language impairments, which matches our finding of one case of relatively strong word learning and one case of relatively weaker word learning. A slight difference between findings is that strong learning from input was noted for these two children with SLI, whereas McGregor and colleagues noted deficits in learning from input by their adults with language impairments. However, McGregor and colleagues noted deficits in learning from input with reference to a normal control group. It is possible that the two children with SLI would show less robust learning from input if compared to a normal control group. Alternatively, the intensity of the treatment may have supported robust learning from input by the two children with SLI. Lastly, KAW022's difficulty maintaining new word forms during memory evolution replicates findings from McGregor and colleagues. McGregor and colleagues note that the pattern of performance they observed is consistent with the procedural learning deficit account of SLI (Ullman & Pierpont, 2005) as well as the phonological loop deficit account of SLI (Gathercole & Baddeley, 1990). Refer to McGregor and colleagues for a more detailed explanation of how these accounts can be integrated with the neurocognitive processing account described in the present paper.

These cases illustrate how clinicians can use treatment data to evaluate the effectiveness of a word learning treatment. In the case of KAW015, the treatment seems to be working with strong learning from input and robust memory evolution. In contrast, the treatment seems to be less effective for KAW022 with strong learning from input but weaker memory evolution. If this were a clinical context, rather than a research context, alteration of the treatment should likely be undertaken for this child along the lines previously outlined (i.e., alter dose, treatment form, or dose frequency).

Conclusion

Word learning is a complex process consisting of at least two neurocognitive processes: learning from input and memory evolution in the absence of input. Detailed investigation of the contribution of these two processes to mastery of new words, either in a research or clinical context, has strong potential to uncover vulnerable points along a path to mastery. Identification of vulnerable points in word learning may assist researchers and clinicians in designing effective educational and clinical practices to accelerate word learning, minimizing or preventing the negative consequences of vocabulary deficits.

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Appendix: Pattern of correct (1) and incorrect (0) responses across eight test points for 732 observations (i.e., 61 participants × 12 novel words) from Storkel et al. (2014)

	Training			Retention	Training			Retention			
Pattern Number	**Day 1: Test 1**	**Day 1: Test 2**	**Day 1: Test 3**	**Day 2: Test 4**	**Day 2: Test 5**	**Day 2: Test 6**	**Day 2: Test 7**	**Day 3: Test 8**	**Number of Observa-tions**	**Percent of Observa-tions**	**Cumulative Percent**
1	1	1	1	1	1	1	1	1	124	16.9	16.9
2	0	1	1	1	1	1	1	1	91	12.4	29.4
3	0	1	1	0	1	1	1	1	82	11.2	40.6
4	0	0	0	0	0	0	0	0	68	9.3	49.9
5	1	1	1	0	1	1	1	1	46	6.3	56.1
6	0	0	1	0	1	1	1	1	37	5.1	61.2
7	0	0	0	0	1	1	1	1	23	3.1	64.3
8	0	0	1	1	1	1	1	1	18	2.5	66.8
9	0	0	1	0	1	1	1	0	17	2.3	69.1
10	0	0	0	0	1	1	1	0	17	2.3	71.4
11	0	1	1	0	1	1	1	0	14	1.9	73.3
12	0	0	0	0	0	1	1	0	14	1.9	75.3
13	1	1	1	0	1	1	1	0	13	1.8	77.0
14	0	0	0	0	0	0	1	0	10	1.4	78.4
15	0	0	0	1	1	1	1	1	9	1.2	79.6
16	1	0	1	1	1	1	1	1	6	0.8	80.5
17	0	1	1	0	0	1	1	0	6	0.8	81.3
18	0	1	0	1	1	1	1	1	6	0.8	82.1
19	0	0	0	0	0	0	0	1	6	0.8	82.9
20	0	1	0	0	1	1	1	1	5	0.7	83.6
21	0	1	0	0	0	0	0	0	5	0.7	84.3
22	0	0	1	0	0	1	1	0	5	0.7	85.0
23	0	0	0	0	0	1	1	1	5	0.7	85.6
24	1	1	0	0	1	1	1	1	4	0.6	86.2
25	0	1	1	0	0	1	1	1	4	0.6	86.7
26	0	1	0	0	1	1	1	0	4	0.6	87.3
27	1	1	1	1	0	1	1	1	3	0.4	87.7
28	1	0	1	0	1	1	1	1	3	0.4	88.1
29	1	0	0	1	1	1	1	1	3	0.4	88.5
30	0	0	1	0	1	0	1	1	3	0.4	88.9
31	0	0	1	0	0	0	0	0	3	0.4	89.3
32	0	0	0	0	0	1	0	0	3	0.4	89.7
33	1	1	1	1	1	1	1	0	2	0.3	90.0

	Training			Retention	Training			Retention			
Pattern Number	Day 1: Test 1	Day 1: Test 2	Day 1: Test 3	Day 2: Test 4	Day 2: Test 5	Day 2: Test 6	Day 2: Test 7	Day 3: Test 8	Number of Observa-tions	Percent of Observa-tions	Cumulative Percent
34	1	1	1	1	1	1	0	1	2	0.3	90.3
35	1	1	1	1	1	0	1	1	2	0.3	90.5
36	1	0	1	0	1	1	1	0	2	0.3	90.8
37	1	0	0	0	0	0	0	0	2	0.3	91.1
38	0	1	1	1	1	1	1	0	2	0.3	91.4
39	0	1	1	0	1	0	1	0	2	0.3	91.6
40	0	1	1	0	0	0	1	1	2	0.3	91.9
41	0	1	1	0	0	0	0	1	2	0.3	92.2
42	0	1	0	0	1	1	0	0	2	0.3	92.4
43	0	0	1	1	1	0	1	1	2	0.3	92.7
44	0	0	1	1	1	0	1	0	2	0.3	93.0
45	0	0	1	0	1	1	0	0	2	0.3	93.2
46	0	0	1	0	1	0	1	0	2	0.3	93.5
47	0	0	1	0	1	0	0	0	2	0.3	93.8
48	0	0	1	0	0	1	0	0	2	0.3	94.1
49	0	0	0	1	1	1	0	1	2	0.3	94.3
50	0	0	0	0	1	0	1	1	2	0.3	94.6
51	0	0	0	0	1	0	1	0	2	0.3	94.9
52	0	0	0	0	1	0	0	0	2	0.3	95.1
53	0	0	0	0	0	0	1	1	2	0.3	95.4
54	1	1	1	1	0	0	0	0	1	0.1	95.5
55	1	1	1	0	1	1	0	1	1	0.1	95.7
56	1	1	1	0	1	0	1	0	1	0.1	95.8
57	1	1	1	0	0	1	1	1	1	0.1	96.0
58	1	1	1	0	0	1	1	0	1	0.1	96.1
59	1	1	1	0	0	0	0	0	1	0.1	96.2
60	1	1	0	1	1	1	1	0	1	0.1	96.4
61	1	1	0	0	0	1	1	0	1	0.1	96.5
62	1	0	1	1	1	1	1	0	1	0.1	96.7
63	1	0	1	0	1	1	0	0	1	0.1	96.8
64	1	0	1	0	1	0	1	1	1	0.1	96.9
65	1	0	1	0	0	1	1	1	1	0.1	97.1
66	1	0	0	0	1	1	1	1	1	0.1	97.2
67	1	0	0	0	0	1	1	0	1	0.1	97.4
68	0	1	1	1	1	1	0	1	1	0.1	97.5
69	0	1	1	1	0	0	0	0	1	0.1	97.6
70	0	1	1	0	1	1	0	1	1	0.1	97.8

Pattern Number	Training: Day 1: Test 1	Training: Day 1: Test 2	Training: Day 1: Test 3	Retention: Day 2: Test 4	Training: Day 2: Test 5	Training: Day 2: Test 6	Training: Day 2: Test 7	Retention: Day 3: Test 8	Number of Observa-tions	Percent of Observa-tions	Cumulative Percent
71	0	1	1	0	1	0	0	1	1	0.1	97.9
72	0	1	1	0	1	0	0	0	1	0.1	98.1
73	0	1	1	0	0	1	0	0	1	0.1	98.2
74	0	1	1	0	0	0	0	0	1	0.1	98.3
75	0	1	0	1	1	1	0	0	1	0.1	98.5
76	0	1	0	0	0	0	0	1	1	0.1	98.6
77	0	0	1	1	1	1	1	0	1	0.1	98.8
78	0	0	1	1	0	1	1	1	1	0.1	98.9
79	0	0	1	1	0	0	1	0	1	0.1	99.0
80	0	0	1	0	1	0	0	1	1	0.1	99.2
81	0	0	1	0	0	1	1	1	1	0.1	99.3
82	0	0	1	0	0	0	1	1	1	0.1	99.5
83	0	0	1	0	0	0	1	0	1	0.1	99.6
84	0	0	0	1	0	1	0	0	1	0.1	99.7
85	0	0	0	0	1	1	0	0	1	0.1	99.9
86	0	0	0	0	1	0	0	1	1	0.1	100.0
				Total					732	100.0	

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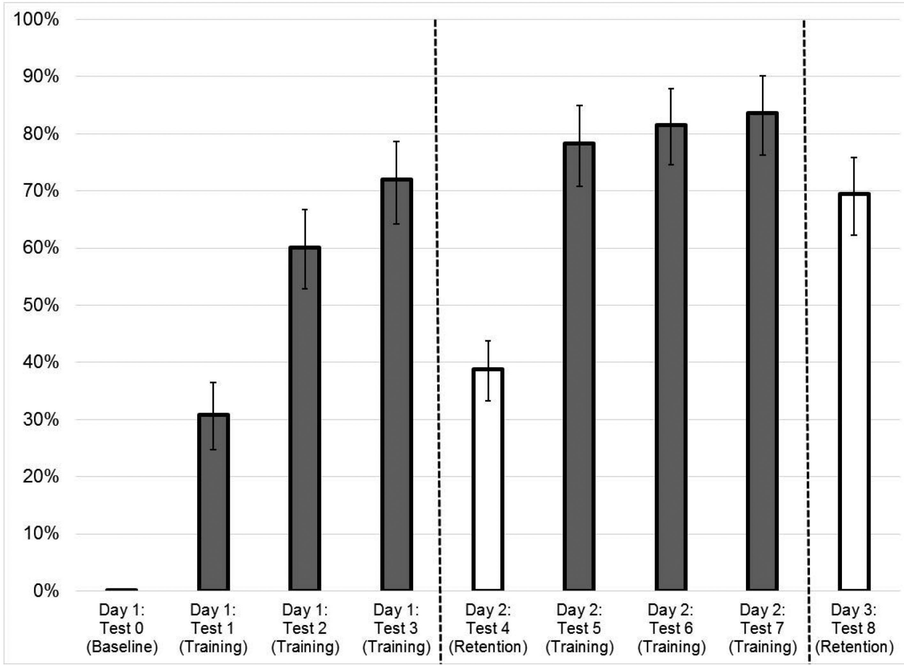


Figure 1.

Mean percent correct for each naming test in Storkel, Bontempo, and Pak (2014). Error bars show the 95% confidence interval. Naming tests tapping learning from input are shown with shaded bars and those tapping memory evolution are shown with open bars. Dashed vertical lines differentiate testing days, which occurred approximately 1-week apart.

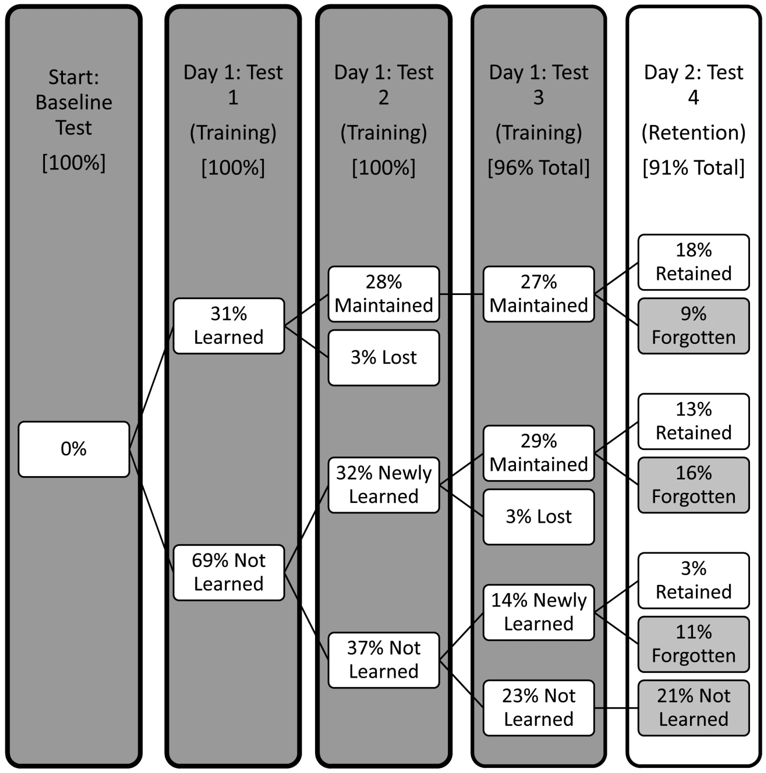


Figure 2.

Pattern of percent correct and incorrect responses for the first day of training consisting of three training-testing cycles (shaded bars) and for the first retention test (open bar) in Storkel, Bontempo, and Pak (2014). Response categories representing 2% or less of the data are excluded from the figure to conserve space. The total data represented in the figure is noted for each test point.

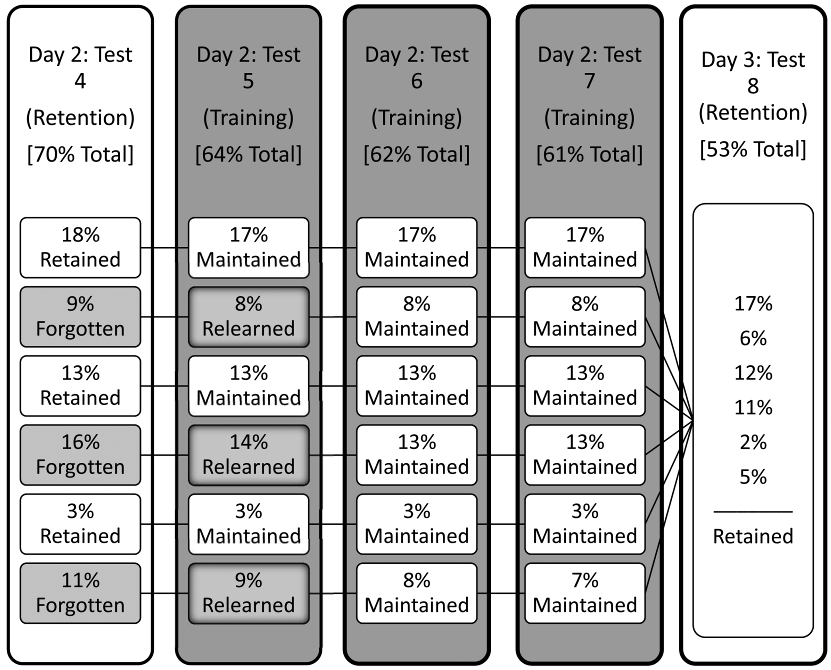


Figure 3.

Only items that were responded to correctly on the first day of training are shown. Pattern of percent correct and incorrect responses for the second day of training consisting of three training-testing cycles (shaded bars) and for the first and second retention tests (open bar) in Storkel, Bontempo, and Pak (2014). Response categories representing 2% or less of the data are excluded from the figure to conserve space. The total data represented in the figure is noted for each test point.

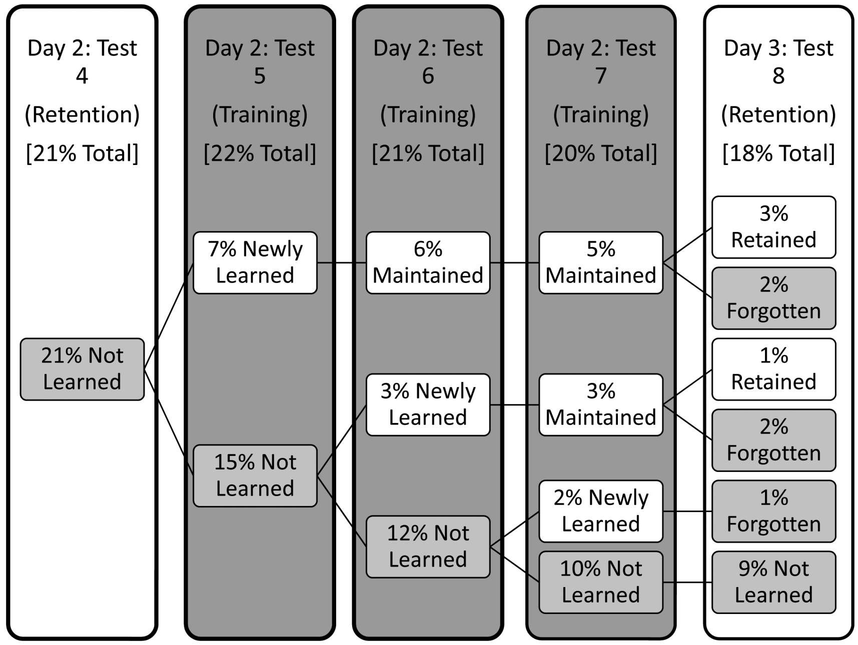


Figure 4.

Only items that were responded to incorrectly at all test points on the first day of training are shown. Pattern of percent correct and incorrect responses for the second day of training consisting of three training-testing cycles (shaded bars) and for the first and second retention tests (open bar) in Storkel, Bontempo, and Pak (2014). Response categories representing 2% or less of the data are excluded from the figure to conserve space. The total data represented in the figure is noted for each test point.

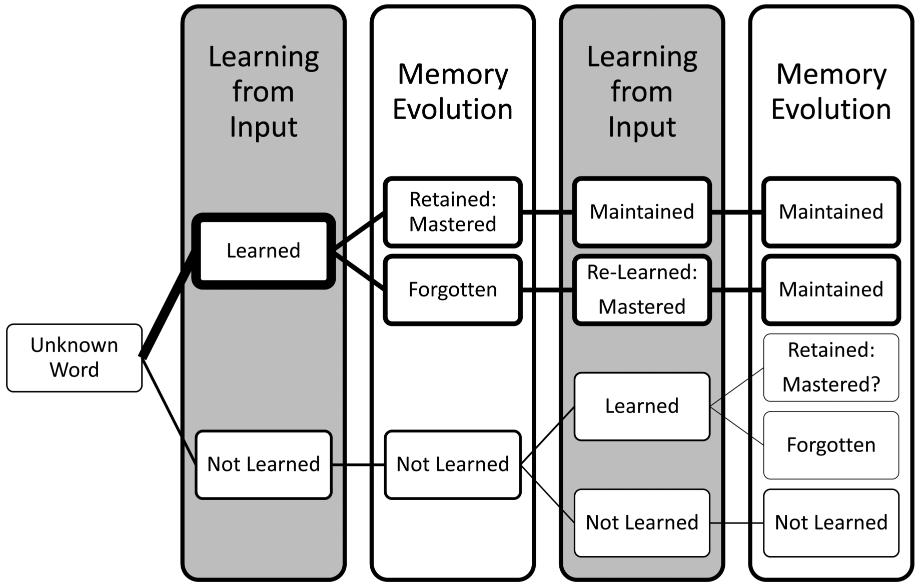
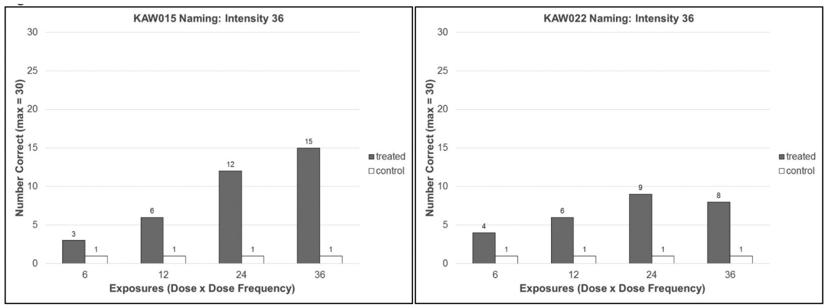


Figure 5.
Summary of pathways to mastery for adult word learning. Frequency of the pathway is indicated by the weight of the lines with heavier lines indicating more frequent pathways.



Correct Treated Words	6	12	24	36
swung	1	1	1	1
embarrassed	1	1	0	1
nervous	1	0	1	1
hauled	0	1	1	1
hooves	0	1	1	1
racket	0	1	1	1
silky	0	1	0	0
furnace	0	0	1	1
grumbling	0	0	1	1
overjoyed	0	0	1	1
sidelines	0	0	1	1
swat	0	0	1	1
prodded	0	0	1	0
scarlet	0	0	1	0
damp	0	0	0	1
discovered	0	0	0	1
glared	0	0	0	1
squinting	0	0	0	1
Newly Learned	3	4	7	4
Maintained	N/A	2	5	11
Total Correct	3	6	12	15

Correct Treated Words	6	12	24	36
invisible	1	1	1	1
snuggled	1	1	1	1
tight	1	1	1	1
flashing	1	0	0	0
squawked	0	1	1	0
horrified	0	1	0	1
gathered	0	1	0	0
marvel	0	0	1	1
awful	0	0	1	0
gulp	0	0	1	0
heaved	0	0	1	0
swaying	0	0	1	0
haddock	0	0	0	1
swift	0	0	0	1
worn	0	0	0	1
Newly Learned	4	3	5	3
Maintained	N/A	3	4	5
Total Correct	4	6	9	8

Figure 6.

Number correct for treated (shaded bars) and control (open bars) words in a picture naming task for two children with Specific Language Impairment (SLI). Bottom panel shows pattern of correct and incorrect responses for treated words for each corresponding child. Treated words that are not shown were never responded to correctly during the course treatment (i.e., 0-0-0-0 pattern of responding across test points).