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Linguistic Self-Correction in the Absence of Feedback: A New Approach to the Logical Problem of Language Acquisition

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Abstract

In a series of studies children show increasing mastery of irregular plural forms (such as *mice*) simply by producing erroneous over-regularized versions of them (such as *mouses*). We explain this phenomenon in terms of successive approximation in imitation: Children over-regularize early in acquisition because the representations of frequent, regular plural forms develop more quickly, such that at the earliest stages of production they interfere with children's attempts to imitatively reproduce irregular forms they have heard in the input. As the strength of the representations that determine children's productions settle asymptotically, the early advantage for the frequent regular forms is negated, and children's attempts to imitate the irregular forms they have observed become more likely to succeed (a process that produces the classic U-shape in children's acquisition of plural inflection). These data show that children can acquire correct linguistic behavior without feedback in a situation where, as a result of philosophical and linguistic analyses, it has often been argued that it is logically impossible for them to do so.

Keywords: Morphological inflection; Semantics; Language acquisition

1. Linguistic self-correction in the absence of explicit feedback

Language is a defining human characteristic. Children of all cultures acquire a native language, and they do so without a need for formal instruction. The consistency and speed with which children acquire language has prompted researchers to question whether language is learned in any meaningful sense. Many theorists have argued that fundamental linguistic skills are inherited, not learned, and that children's linguistic endowment is more genetic than cultural (e.g., see S. R. Anderson & Lightfoot, 2000).

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A strong motivation for this belief is a logical problem that appears to rule out theories of language acquisition based solely on learning. The problem is rooted in the language children are exposed to in acquisition (the input). Analyses suggest this is an inconsistent and incomplete guide to the language to be acquired, such that a learner will inevitably make incorrect hypotheses about the nature of the language they are learning. Further, it has appeared that learners cannot recover from these erroneous inferences without corrective feedback, and that children do not get the kind of feedback required (Brown & Hanlon, 1970). Finally, there is even evidence that when feedback is provided, children ignore it (Marcus, 1993). Thus, according to what has become known as the "logical problem of language acquisition" (LPLA), children cannot acquire language simply by attending to the input. Therefore, the idea that language can be learned purely from experience is often regarded as having been effectively disproved (Baker, 1979; Gold, 1967; Pinker, 1989; for a review, see MacWhinney, 2004). Many language acquisition theorists thus see their goal as uncovering the constraints and parameters that comprise the innate "universal grammar" that serves to restrict the space of possible natural languages, thus making language learning a tractable enterprise (Chomsky, 1965; Pinker, 1994).

A classic formulation of this problem is provided by Pinker (1989; see also Berwick, 1985, and Pinker, 1984) and is depicted in Fig. 1. According to this formulation, the child's task in attempting to learn a language is characterized as having to correctly hypothesize the grammar of the adult language to be learned (strictly speaking, the child's task is to guess the set of grammatical sentences that comprise that language; Gold, 1967).

Possible languages are depicted as circles corresponding to sets of word sequences, and four logical possibilities for how a child's language might differ from adult language are shown. In (a), the child's hypothesis language, H, is disjoint from the language to be acquired (the "target language" [T]). In terms of noun usage, the domain on which we concentrate in this article, this corresponds to the state of a child learning English who cannot produce any well-formed noun plurals (e.g., the child might say things like "I like mouses" but never "I like mice"). In (b), the sets H and T intersect, corresponding to a child who has learned some nouns correctly but others incorrectly (e.g., the child uses nouns like MICE alongside incorrect words like GOOSES). In (c), H is a subset of T, which means that the child has mastered usage of some but not all English noun plurals and never uses forms that are not part of English. Finally, in (d), H is a superset of T, meaning that the child has mastered all

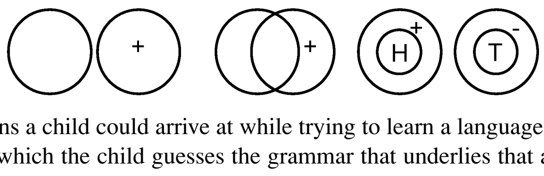

Fig. 1. Four logical situations a child could arrive at while trying to learn a language (where language learning is assumed to be a process in which the child guesses the grammar that underlies that adult target language). *Note*: Each circle represents the set of sentences constituting a language. H = the child's "hypothesized language"; T = the adult "target language"; + = a grammatical sentence in the language the child is trying to learn; – = an ungrammatical sentence (Pinker, 1989).

English nouns but nevertheless produces some forms that are not part of the English language (i.e., the child says both MOUSES *and* MICE interchangeably).

How might a child holding one of these hypotheses achieve the linguistic competence of an adult? According to this approach, in the first three cases (a–c), the child can learn its hypothesis is incorrect by hearing positive evidence: sentences that are in T but not in H. In (d), however, the correct pattern cannot be learned in this way; the standard argument runs because the child's hypothesis contains both the correct and incorrect forms, and further positive evidence will always be compatible with the child's hypothesized language. Instead, if one assumes that language learning proceeds within this explicit hypothesis-testing framework, then negative evidence—explicit marking of the inappropriateness of ungrammatical sentences—is required to successfully learn in this situation. And since it is claimed that children do not receive reliable correction from their parents (Brown & Hanlon, 1970; although Chouinard & Clark, 2003, present evidence that parents may provide more feedback than is often supposed), and they do typically go through a phase in which they produce both MICE and the ungrammatical MOUSES, it has appeared that some mechanism other than explicit correction must cause them to abandon these hypotheses and gain adult competence. This mechanism is usually assumed to be innate and specific to language. For example, Marcus et al. (1992) propose an innate "blocking" mechanism that suppresses the +*s* noun pluralization rule and reduces the likelihood of erroneous regular forms (such as MOUSES) being produced as memory for correct irregular forms (such as MICE) strengthens by repeated exposure.

If one accepts the assumptions of the "hypothesis testing" approach to language learning it presupposes, the LPLA poses an insuperable problem for accounts of grammatical acquisition that do not assume innate language-specific mechanisms (Seidenberg, 1997). However, a number of other views of language acquisition have been put forward that stand in some contrast to the hypothesis-testing framework. For example, item-based theories of language acquisition (Goldberg, 2003; Tomasello, 1999, 2003) contend that language acquisition does not involve a learner guessing the set of grammatical strings that comprise the adult language (as per Gold, 1967), but instead that language learning is better conceived of as a process in which a child slowly learns a set of social and cognitive competencies that can be more accurately characterized in terms of general learning mechanisms. According to such accounts, these general learning mechanisms allow children to acquire knowledge about specific constructions—for example, that +*s*marks the plural semantic difference between DOG and DOGS—and that this knowledge can be incrementally extended to other constructions based on analogies that are drawn: for example, that adding +s to CAT is an effective way of denoting multiple cats. In this way the features of specific, rote-learned items are gradually incorporated into more general grammatical constructions over the course of language acquisition.

Various solutions to the LPLA that do not rely on innate, language-specific mechanisms have been proposed from this perspective (see MacWhinney, 2004). In particular, it has been shown that recovery from over-regularization (and the particular U-shaped pattern of this recovery, in which improvement seems to follow a period of decline in correct performance) can be modeled as an inherent feature of the way in which the strengths of the representations of frequently and infrequently encountered items develop in a connectionist network (Plunkett & Juola, 1999; Plunkett & Marchman, 1991, 1993; Rumelhart & McClelland, 1986).

Although these models successfully solve the LPLA, the way they do so has been the focus of much criticism. First, it is argued that their success is largely dependent on the specific training regimes they are exposed to (Marcus, 1995; Marcus et al., 1992; Pinker, 1999, 2001; Pinker & Prince, 1988; Taatgen & Anderson, 2002). Second, it is argued that the use of back-propagation algorithms (Plunkett & Juola, 1999; Plunkett & Marchman, 1991, 1993; Rumelhart & McClelland, 1986), in which learning in networks relies on calculating the error between the actual and intended output of a system, is psychologically unrealistic (Pinker, 2001; Taatgen & Anderson, 2002). Back-propagation assumes children "monitor the error associated with individual pattern tokens" they produce (Plunkett & Marchman, 1993, p. 29), yet children's notoriously poor source memory (Bruck & Ceci, 1999) and their poor ability to distinguish between correct irregular forms and over-regularizations (Kuczaj, 1978) has raised questions about the validity of this assumption (Taatgen & Anderson, 2002). A further question raised by the use of back-propagation to solve the LPLA is that of parsimony: If a child possesses a correct representation of the final state of the linguistic structure to be learned in memory, why does the child not use that representation directly to govern his or her behavior, as opposed to using it to tune a second representation that is actually responsible for generating behavior (Pinker, 1999, 2001; Pinker & Prince, 1988)?

Thus, although numerous mechanisms have been proposed for how children might *in principle* successfully resolve the LPLA, the question of whether they *actually do so* in the ways proposed by the various models remains an open and intensely debated question (Marcus, 1995; Pinker, 1999, 2001).

So, how in fact do children solve the LPLA? To shed light on this question, we focus here on the influence of semantics in determining the inflections of linguistic forms (in this case, English plural nouns), an aspect of morphosyntax that has only recently become a major focus of research (Glass & Lau, 2003; Joanisse & Seidenberg, 1999; Moscoso del Prado Martín, Kostic, & Baayen, 2004; Ramscar, 2002; see also MacWhinney & Leinbach, 1991; previous models of morphosyntactic processing tended to focus solely on phonology—cf. Albright & Hayes, 2003; Plunkett & Marchman, 1991, 1993; Rumelhart & McClelland, 1986; Taatgen & Anderson, 2002). Correct irregular plural marking is particularly difficult to acquire in English. Irregular *verbs* have high token frequencies, even though they are rare as types, whereas irregular plural nouns are rare as *both* types and tokens (irregular plurals have a token frequency of around only 2%; Plunkett & Juola, 1999). The development of irregular plurals in English is thus protracted (9-year-old children have not mastered many common irregular plurals; see Graves & Koziol, 1971), allowing considerable scope for experimental interventions to be made, and their effects to be measured, across its span.

In examining how semantic and phonological factors might interact in the learning of noun plurals, we have developed a model of the way that noun forms could be acquired through simple principles of imitative learning. The model attempts to simulate the way that semantic mappings to phonological noun forms develop in acquisition, and it makes a novel and surprising prediction: that at an appropriate stage of development, children will recover from superset grammars (e.g., production of over-regularized forms such as mouses) and converge on adult competence without any requirement for additional input or any form of feedback.

2. The model

As with other memory-based models of children's acquisition of inflection, the model we present treats cases in which a child produces over-regularized and correct forms of irregular items somewhat interchangeably as a transitional phase in the learning of a probabilistic response, rather than as evidence that the child has actually hypothesized a "superset grammar." The model does not treat, say, *mouses* as an explicit hypothesis of the child; rather, it assumes that "*mice* is the appropriate name for multiple instances of *mouse*" is learned and is in a child's memory. Thus, we assume that when, for example, a child is asked to name a picture of mice, the child's memory activates the word *mice* imitatively because this is the phonological form the child has learned to produce in response to the semantics of the situation.[1] We thus assume that in a language such as English, where multiple instances of count nouns are usually named using a different phonological form to single-count nouns, a child must learn to discriminate between single and multiple items when naming (it appears that any theory of language acquisition must assume that children learn to discriminate between items in terms of their numerosity if they are to learn and produce plural and singular forms for them, and it seems reasonable to us to assume that a child could *learn* to select between single and plural responses based on a numerosity discrimination because similar abilities have been demonstrated in other primates, e.g., Hicks, 1956; as well as in animals as varied as pigeons [e.g., Emerton, Lohmann & Niemann, 1997], crows [e.g., Zorina & Smirnova, 1996], rats [e.g., Capaldi & Miller, 1988], and dolphins [e.g., Kilian, Yaman, von Fersen, & Gunturkun, 2003]). Because the critical cue in selecting between singular and plural forms will be relative numerosity, we also assume that the task of naming multiple items will result in some activation of other phonological forms used to name plurals (see MacWhinney, 2004, and Stemberger & MacWhinney, 1988); and because of the type and token dominance of regular nouns in English, these will largely be plural forms that resemble their associated singular forms but that end in +*s*. Early in learning, the high frequency of regular items in English will result in rapid strengthening of the +*s*plural response, and thus even weak activation of these competing forms may drown out the correct activation of *mice*. However, owing to the negatively accelerated, asymptotic nature of human learning (J. R. Anderson & Schooler, 1991; Ebbinghaus, 1913), the frequency advantage of plural +*s* will be ameliorated over time as its associative strength asymptotes, after which irregular representations that are still approaching their asymptote will strengthen against it.

Apparent "superset hypotheses" thus arise in the model as a natural consequence of learning, and language-specific mechanisms are not required in order to explain their resolution. The model is therefore simpler and makes fewer ontological commitments than traditional generative approaches to this problem (e.g., see Grimshaw & Rosen, 1990).

The model assumes that noun items are represented as exemplars in memory, with each exemplar comprising an associative link between a semantic and a phonological component. For example, the plural noun CARS is represented by one such couplet, encoding the association between the general semantics of cars, including their plurality, and the phonological form /cars/ (Slobin, 1997). Learning takes place either when a couplet is explicitly reinforced (e.g., an object is labeled as a CAR) or when the couplet is reactivated by subsequent priming of either its semantics or phonology (as in the experiments reported below; see also Roediger

& Karpicke, 2006, and Tulving, 1967). When activated, the associative couplets are strengthened as a negatively accelerated function of the current stage of learning (J. R. Anderson & Schooler, 1991; Ebbinghaus, 1913). Couplets also receive a boost in learning from other items that are in the same phonological or semantic family as the item being learned because of positive transfer from similar couplets through spreading activation (McClelland & Rumelhart, 1986; Stemberger & MacWhinney, 1988). Because the conjunction of a final sibilant and plural semantics is common to regular plural nouns, this will cause regulars to be learned more rapidly than irregulars (Brown, 1973).

For the sake of simplicity, we assume that each noun in the model is encountered equally frequently (although this assumption could easily be altered in order to model item-specific effects of the sort documented by Plunkett & Marchman, 1991, 1993) and that each item is encountered once per epoch. In accordance with these assumptions, the change in associative strength as a result of training on a given trial is modeled in the following fashion:

$$\Delta a_{i,t} = \eta(1 - a_{i,t})\left(1 + s \sum_{j \in F, j \neq i} a_{j,t}\right). \tag{1}$$

Here, $a_{i,t}$ is the association strength between the semantics and phonology of couplet i at time t, η is a learning rate parameter, s is a spreading activation parameter, and F is the set of items in memory that come from the same phonological family as item i (e.g., the family consisting of all plural forms ending in +*s*). The rate of learning thus depends on η; the spreading activation parameter, s (where $0 < s < 1$); and also the degree to which the other items belonging to the same phonological family have themselves been learned.

The actual activation level on a given trial is thus defined as the activation on the previous trial plus the "delta" of association strength on the previous trial:

$$a_{i,t} = a_{i,t-1} + \Delta a_{i,t-1}. \tag{2}$$

Fig. 2 shows example learning curves for a regular and an irregular noun.[2] As can be seen, the association strength for a given regular item does indeed grow more rapidly than that for an irregular item because of the increased rate at which the regular form is mastered as a result of positive transfer from other regular items in memory.

A crucial aspect of the model is the way in which we propose competition affects the memory process that underlies *productions* of noun forms. When a particular set of semantic cues is presented, we assume that two distinct factors determine the model's (and the child's) response: first, the direct *imitative* memory response that simply reactivates the phonological form a child has previously learned to associate with the semantic cue (if prompted to make a production when presented with the semantics a child has learned to associate with a form, the child will naturally attempt to produce that form); and second, supporting and competing responses that derive from noun forms with similar semantics to the presented cue.

If the child is presented with multiple instances of an object, we assume that this will activate some representation for which numerosity is an important cue (see above) in the child and that this, in turn, may lead to the activation of other plural forms. Whether this activation serves to support or compete with the primary response will depend on whether the phonological forms that are activated by the spreading activation of plural semantics share features with the

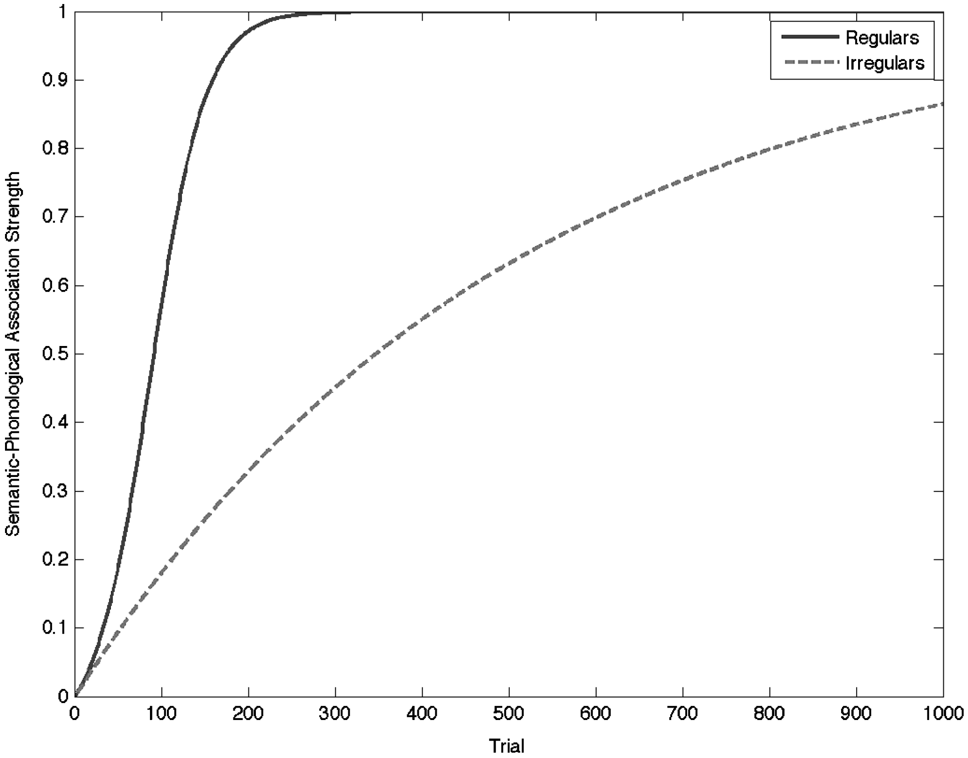

Fig. 2. Plots showing the rate at which the semantic–phonological couplets representing a regular and an irregular item are learned.

correct phonological form the child imitatively activates based on prior learning: If the form is a regular plural, it will receive support from other forms that also associate plurality with a final sibilant.

This competition can be modeled through a simple rule in which the correct response is activated by the semantic cues presented, and other responses that support or compete with the imitative response are also activated (albeit in a weaker form) in virtue of their sharing plural semantics. Competition comes from the memory items that are also activated by the semantics of the situation but which correspond to different phonological forms and is a function of the degree to which these competing semantic-phonological couplets have been learned. The rule implementing the imitation signal is as follows:

$$\text{Imitation}_{i,t} = \frac{a_{i,t} + s \sum_{j \in F, j \neq i} a_{j,t}}{1 + \sum_{j \in F, j \neq i} s}, \tag{3}$$

where $a_{i,t}$ is the direct association between the semantic cue and the phonological form as given by Equation 1, s is the spreading activation parameter, and F is again the set of items in the same phonological family as the learned item and which thus have congruent responses. The denominator of the aforementioned equation is simply a normalization term, which ensures that the strength of the imitation signal is bounded in the range 0 to 1.

The rule implementing the competition signal in the model is as follows:

$$\text{Competition}_{i,t} = (1 - \text{Imitation}_{i,t})\frac{s \sum\limits_{j \notin F} a_{j,t}}{\sum\limits_{j \notin F} s}. \tag{4}$$

This rule states that the potential for a competing response diminishes as the correct imitative response becomes better learned (bounding the amount of activation associated with a given response; e.g., see Rescorla & Wagner, 1972) and is also a function of how well the competing couplets have been learned and the spreading activation parameter of the model. Again, the denominator of the fraction is a normalization term that ensures that the strength of the competition signal is bounded in the range 0 to 1.

Curves depicting the support and competition signals for regular and irregular items in a simulation with 1 irregular and 50 regular items are shown in Fig. 3.

In our model, we subtract the competition signal from the imitation signal to generate what we term a response propensity for regular and irregular items (see Fig. 4). This is simply a measure indicating the strength of evidence for either reproducing the learned form (signal values greater than 0) or over-regularizing (signal values less than 0). Note that the response signal for the regular items tends to be stronger than that for the irregular items (as a result of the larger set size of regular nouns and the corresponding support they receive), and also that for the irregulars the model predicts initially increasing rates of over-regularization that naturally correct themselves with increased experience of language. We demonstrate in the appendix that this U-shape in response propensity is a strong prediction of our model and is largely independent of the parameter values that are chosen in implementation.

Clearly, the factors influencing the forms a child will actually produce in a given situation are numerous and will include at a minimum the current context, the totality of the child's state of learning, and even perhaps a natural disposition to do nothing when the support for a specific course of action is weak. However, under some simple assumptions it is possible to illustrate how the response propensities produced by our model could be manifested as probabilities of production, by using Luce's Choice Axiom (Luce, 1959, 1977). The Choice Axiom states that the probability of a response is approximately equal to the evidence in support of that response divided by the sum of evidence for all possible responses; although its exact validity has been questioned in certain domains, it will suffice in the present context to allow us to show how direct behavioral predictions can be generated from our model. In order to do this we have to make some assumptions about the possible options available to a child when asked to inflect a noun form. So far we have been concerned only with whether the child will favor the imitation or competition in producing its inflected forms. However, there is a third possibility that is very important at the beginning of learning: that the child simply elects to do nothing. This is important because we assume that before the child has any experience of language, any attempt to elicit a plural noun from the child will necessarily end in total failure (in other words, the efforts of the experimenter will be met, at best, with

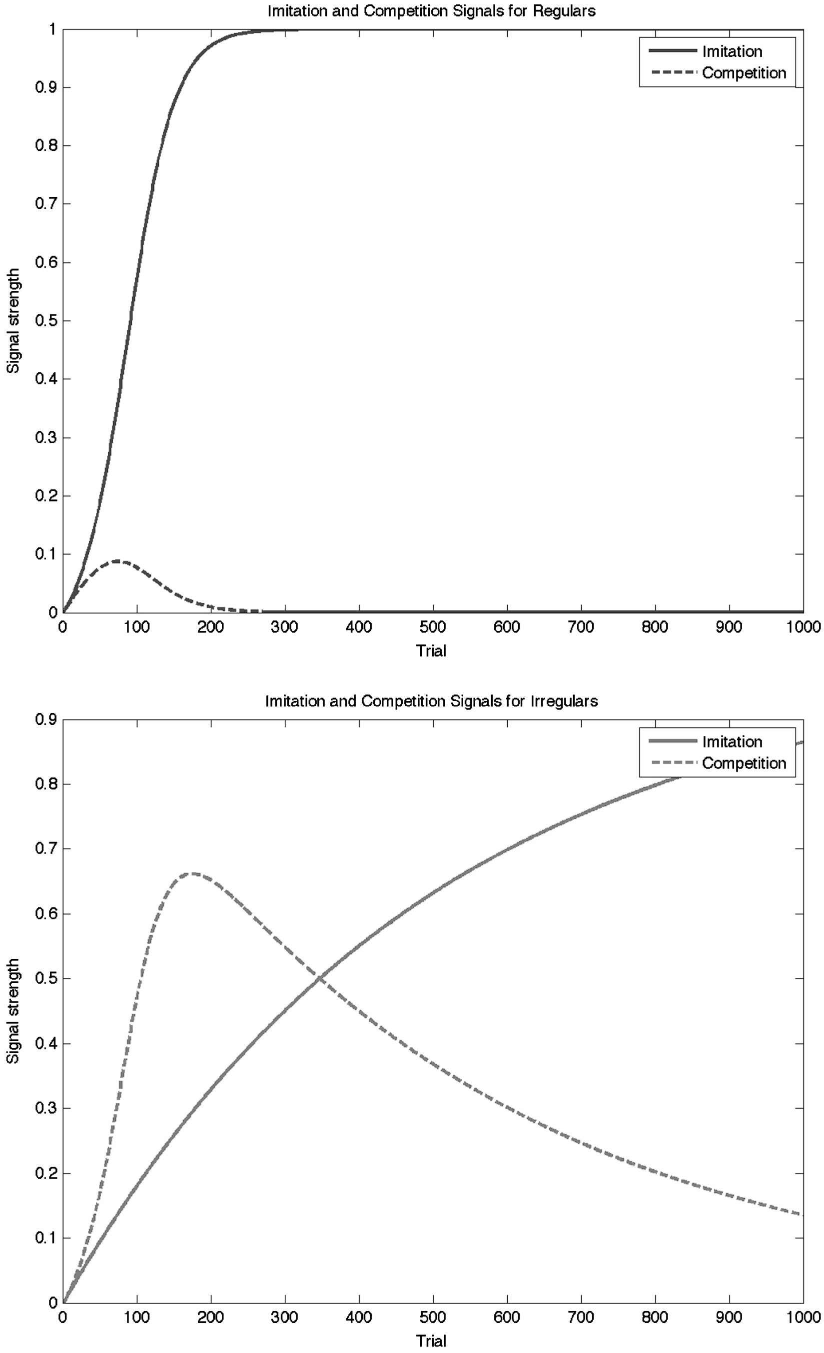

Fig. 3. The strength of the imitation and competition signals for regular and irregular items. *Note*: For the irregular items, the competition signal dominates early in training but is eventually surpassed by the imitation signal, whereas for the regular items the imitation signal dominates at all stages of learning. This is a direct consequence of the regular family having more members, which means that the irregular items have to overcome a stronger competition signal from this family of congruent responses.

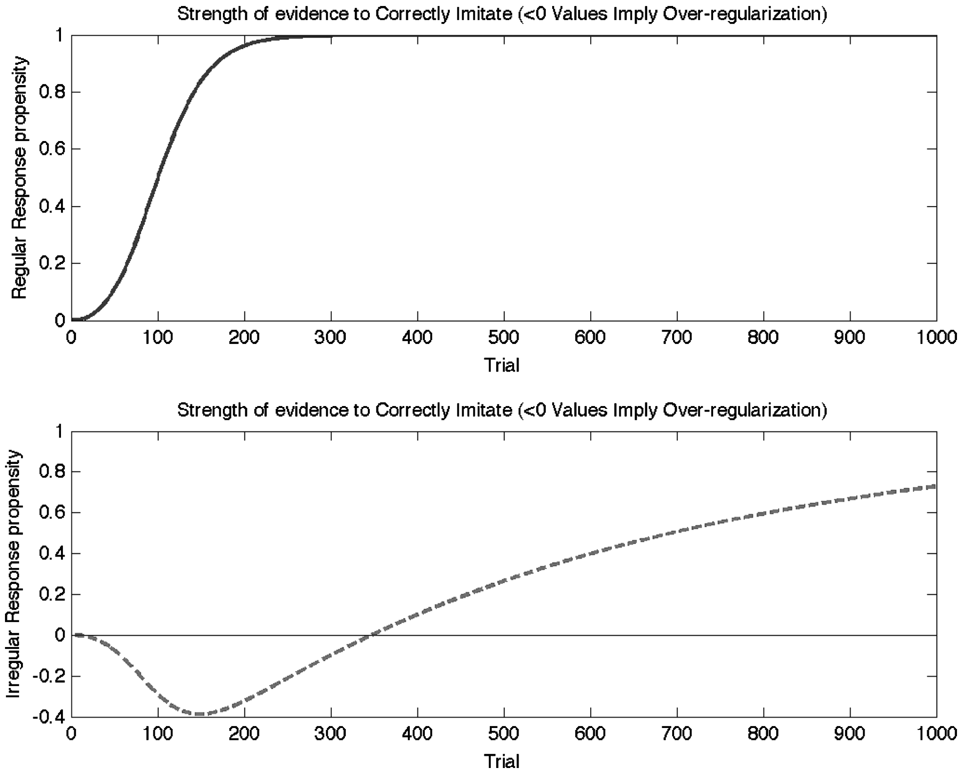
Strength of evidence to Correctly Imitate (<0 Values Imply Over-regularization)

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Fig. 4. Plots showing the response propensity of the model for regular and irregular items. Note the U-shaped trend in the irregular items.

a quizzical stare). The simplest way to represent this in the model is to assume that that the child begins with a small amount of "evidence" in favor of producing nothing, and that this evidence needs to be overcome before the child will attempt any verbal production. Given this we can use the Choice Axiom to define the following:

$$P(\text{Correctly Inflecting Form } i \text{ at time } t) = \\ \text{Imitation}_{i,t}/(\text{Imitation}_{i,t} + \text{Competition}_{i,t} + \text{No} - \text{Response}_{i,t}). \tag{5}$$

For simplicity, we assume that the evidence in favor of No-Response is constant across Time, and identical for both regular and irregular forms, although in a more sophisticated model one could imagine that the child comes to learn that a failure to respond is not socially appropriate and hence that this value diminishes over time. We set the No-Response evidence to 0.025, a relatively small value compared to the evidence produced for the regular and irregular inflections after a little learning, to indicate that the child learns fairly rapidly that some sort of verbal response is desirable in an elicitation context. The probability of correctly inflecting regular and irregular forms as a function of time, as predicted by Equation 5, is shown in Fig. 5.

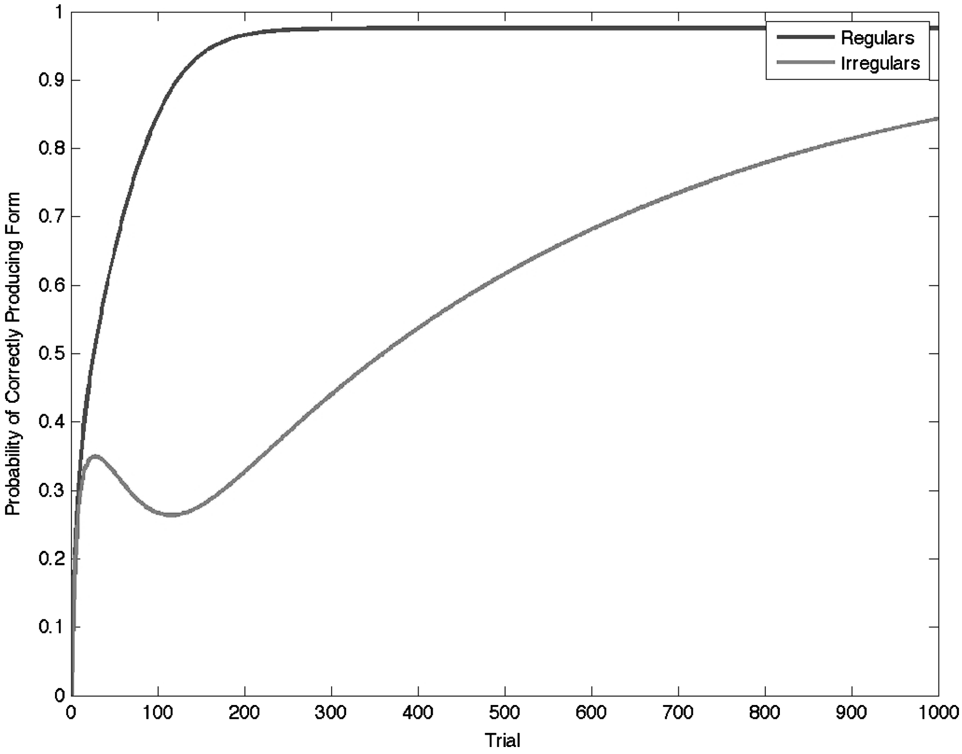

Fig. 5. Plot showing the probability of correctly producing regular and irregular forms after varying amounts of experience. Note the clear U-shaped trend in the learning profile of the irregular plurals predicted by the model, and that production performance on regular forms is always predicted to be better than production performance on irregular forms.

One can see that the regular forms are learned more rapidly than the irregular forms and that regular learning proceeds in an uninterrupted, smooth fashion. However, the most striking aspect of this plot is the U-shaped learning function predicted for the child's performance on the irregular forms, which is consistent with what has been observed empirically in children's inflection behavior (see Marcus et al., 1992; McClelland & Patterson, 2002; Rumelhart & McClelland, 1986). The presence of the U-shaped curve, whether manifested in the response propensities or the production probabilities, allows us to make a clear prediction from the model that we can test.

In the early stages of acquisition, the model predicts that children should actually get worse at inflection in a repeated plural elicitation task on a normal sample of nouns (in which the token frequency of regular forms outweighs that of individual irregular forms) because in performing the task the child will encounter far more tokens of regular nouns than she will tokens of the individual types of irregular nouns, resulting in a more rapid strengthening of the representation of the common features of regular items. In this situation, the imitative improvements to irregular production that we predict arise from repeated reactivation of a learned couplet will only manifest themselves behaviorally at around the point that the regular items are learned to asymptote (at this point, the frequency advantage the regular forms enjoy will begin to diminish). A direct and quite counterintuitive prediction of the model, therefore, is that children's irregular inflection performance can improve in an elicitation task even when (a) they are producing over-regularized forms, and (b) they are provided with no external feedback about their performance. We test this prediction in the studies reported below.[3]

3. Study 1

To determine whether children who over-regularize in production nevertheless have some representation of the correct irregular forms in memory, as our model proposes, we tested the ability of 3- to 5-year-old children to produce, recognize, and comprehend six irregular plural nouns. At this age, children have fully mastered regular plural inflection (Brown, 1973; de Villiers & de Villiers, 1973) but often over-regularize irregular plural nouns (Graves & Koziol, 1971).

Three tasks were designed to manipulate the cues available to the children to probe the underlying causes of over-regularization. In the production task, children were presented with a picture of a noun item and had to name it (retrieve the phonological response to the semantic cue). In the recognition task, the children were shown a picture depicting a plural noun (e.g., a collection of mice). One puppet then labeled this with an over-regularized form (e.g., MOUSES), and a second puppet labeled it with the correct form (e.g., MICE). The children then had to indicate which source a third puppet should listen to in order to learn the correct word for the picture. Finally, comprehension knowledge was assessed by asking the children to indicate which picture corresponded to a given word.

3.1. Participants

Participants were sixteen 3- to 5-year-old (8 boys and 8 girls, mean age 4 years, 2 months) pupils at Bing Nursery School, Stanford, California.

3.2. Procedure

Elicitation Task In this task, the children were asked to help a cookie monster puppet learn to name a series of plural nouns. In all, 6 regular plurals and 6 irregular plurals were selected (the 6 irregular nouns and their plurals were FOOT/FEET, TOOTH/TEETH, CHILD/CHILDREN, MOUSE/MICE, SNOWMAN/SNOWMEN, and GOOSE/GEESE, and constituted items from each of the families of irregular plurals that young children reliably learn to master).[4] The children were seated next to the experimenter, shown pictures of each item in single and then multiple forms on a laptop computer screen, and then asked to tell the monster the names of these items.

Recognition Task After completing the elicitation task, the children were then shown a series of films of puppets describing pictures of objects. In the first two trials, the puppets alternately described an object either correctly or incorrectly (e.g., a car was either described as a 'car' or as a 'plane'; a chair as a 'chair' or a 'table'), and the children were asked to indicate which of the two puppets was giving the correct names for the objects to a third "student" puppet. The children then repeated this task for the six irregular plurals, which the puppets either named in their correct or over-regularized forms (e.g., MICE vs. MOUSES). To reduce response bias, different puppets were used for each trial film (in piloting, we found that children tended to "adopt" a particular puppet and stick with it), and the side of the correct answer (left or right) was counterbalanced between trials.

Comprehension Task Finally, the children were shown six 3 × 2 arrays, one at a time, each of which contained plural and singular images of one of the target nouns along with plural and singular images of two distractor nouns. The children were asked to show the cookie monster puppet the item(s) that corresponded to the singular and correct irregular plural forms of the target items (in other words, the children were asked to show the puppet which picture corresponded first to MOUSE and then which to MICE, etc.).

Testing took place in a dedicated child study laboratory. Trials were videotaped and transcribed independently by two coders who later met to resolve any coding discrepancies.

3.3. Results and discussion

Consistent with the idea that children who over-regularize in production nevertheless possess representations of correct irregular forms, we found large discrepancies between our participants' performance in the production and the recognition and comprehension tasks.

Elicitation Task Childrenproduced correct irregular plurals (19.7% of productions) significantly less often than over-regularizations (50.8%), $t(11) = 2.313$, $p < .05$, with the remaining 29.5% of productions being zero-marked forms (i.e., they produced a form without a plural marker, such as MOUSE, when a plural was elicited. (Four children failed to provide correct answers to both of the comprehension tests in the recognition task—e.g., they indicated that car was the correct name for a plane, or vice versa—and were eliminated from this and all subsequent analyses; the mean age of the 12 children analyzed remained at 4 years, 2 months.)

On the whole, the children produced singular forms successfully for MOUSE, SNOWMAN, GOOSE, and CHILD. However, the average rate at which plural forms were produced when a singular form was elicited for FOOT and TOOTH was 31.3% as opposed to 1.6% for the other four items. One reason for this may be that of the irregular nouns tested in this study (which represents the complete set of families of these nouns available to children of this age), FEET and TEETH are massively more frequent in language in their plural than in their singular forms. Whereas CHILD, MOUSE, GOOSE, and MAN are neither plural nor singular dominant in the input (the ratio between plural and singular forms in each case is less than 1:2), in use the plural forms of TOOTH and FOOT outnumber singular forms by more than 4:1 (Francis & Kucera, 1982). This suggests that children's use of FEET or TEETH may not be reliably diagnostic of their having acquired the correct singular and plural semantics for TOOTH/TEETH and FOOT/FEET, because children often use the plural forms FEET and TEETH to mark both plurality and singularity (Clark, 1993).

- **Recognition Task** The children correctly identified the adult form (rejecting the over-regularized form) in 66.3% of the recognition trials (significantly more than both production, $t[11] = 9.719$, $p < .0001$; and chance, $t[11] = 3.630$, $p < .005$).
- **Comprehension Task** Children successfully comprehended 80.6% of the adult forms, correctly mapping them to the appropriate images (a significant improvement on production, $t[11] = 7.637$, $p < .0001$; and chance, $t[11] = 5.272$, $p < .001$).

An analysis of the relation between the children's productions and their performance on the recognition task revealed that children's production of an over-regularized form was a poor predictor of their preferring either the over-regularized (probability of .55) or the correct irregular (probability of .45) form, confirming a dissociation between recognition and production knowledge. However, production of either a zero-marked or a correct form was a good predictor of children's ability to recognize the appropriate adult form in this task (the probability that a child producing a zero-marked form recognized the adult form was .85; for items that could be compared, zero-marked form production better predicted correct recognition than over-regularized production,$t[4] = 3.907$, $p < .02$; for correct production, these figures are $p = .81$ and $t[5] = 3.378$, $p < .02$). This suggests that although high rates of zero marking are traditionally assumed to be an indicator of poor linguistic knowledge (Pinker, 1999), they may also occur as children begin to master aspects of language such as pluralization, perhaps as a result of competition as a child's linguistic representations strengthen. Although children's age and their errors in the comprehension task were, as one would expect, negatively correlated, there was a significant positive correlation between age and children's production of more zero-inflected forms (see Figs. 6 & 7).

To further explore this relation, the error data from the 12 children on the production and comprehension tasks (which involved exactly the same items) were divided into two groups based on age. The younger group (mean age = 3 years, 9 months) produced fewer zero-marked inflections ($M = 1$) and more comprehension errors ($M = 3.5$) than the older group (mean age = 4 years, 7 months; mean zero inflections = 2.5; mean comprehension errors = 1). A repeated measures analysis of variance (ANOVA) with age as the between-subject factor revealed the interaction between zero-marking and comprehension errors to be significant, $F(1, 10) = 8.087$, $p < .02$.

4. Study 2

Having established that children who over-regularize plurals in production nevertheless have representations of the correct adult forms in memory, Study 2 sought to test the prediction of the imitation model that these children would self-correct over-regularization errors simply through the process of repeating incorrect forms.

4.1. Participants

Participants were ten 5- and 6-year-old (6 girls and 4 boys, mean age 5 years, 10 months) pupils at Mary Erskine's School, Edinburgh, Scotland.

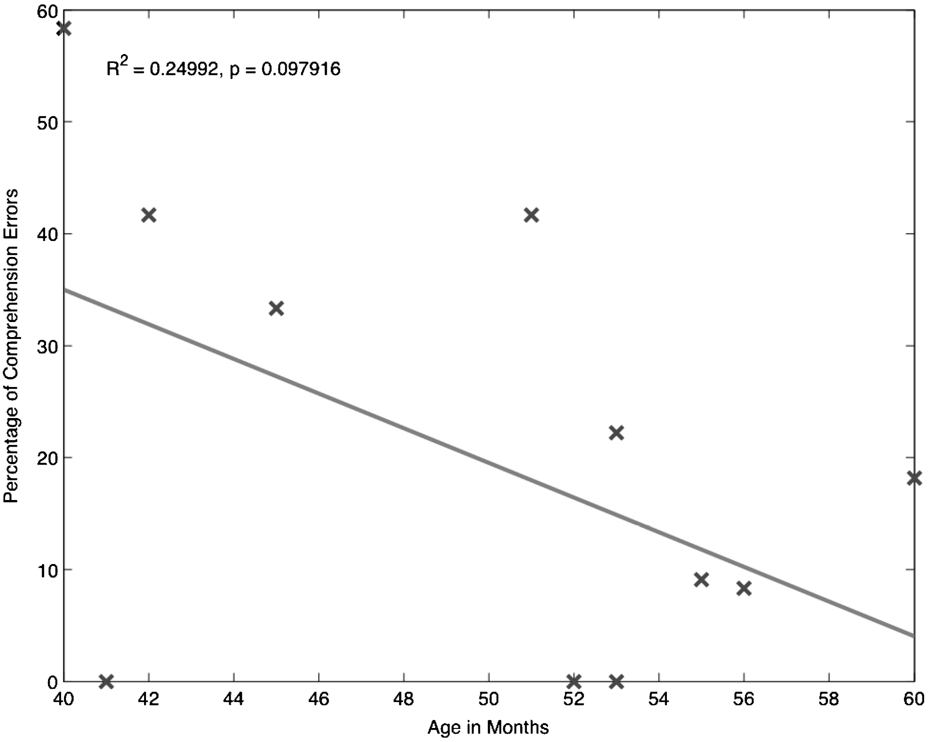

Fig. 6. The relation between age and comprehension errors in Study 1.

4.2. Method

In this task, children were asked to help a cookie monster puppet learn to name a series of plural nouns. The children sat with the experimenter and named 18 regular and 6 irregular plural nouns (MOUSE–MICE, CHILD–CHILDREN, SNOWMAN–SNOWMEN, GOOSE–GOOSE, TOOTH–TEETH, and FOOT–FEET) first from singular and then from plural depictions that were presented on a laptop computer. Six of the regular nouns (RAT, DOLL, COW, DUCK, EAR, and HAND) were included as semantic correlates of the 6 irregulars, whereas the inclusion of the other 12 was intended to reflect the numerical dominance of regular plurals in ordinary input while keeping the task manageable for 6-year-old children.

Irrespective of the plural form the child produced, they were provided with encouraging feedback (the child was always told that they were doing very well and being a great help to the puppet). This kind of non-conditional encouragement is a standard procedure in our lab for non-linguistic tasks to ensure both that the children feel comfortable in the experimental setting and to encourage them to complete the task in its entirety. Although the question of whether children are receptive to linguistic feedback remains controversial, we felt that this procedure would further ensure that the children had no reason to doubt the acceptability of their output in this instance (which might have, artificially, induced some change in the linguistic performance of the children). At the end of each trial the puppet was asked if he had

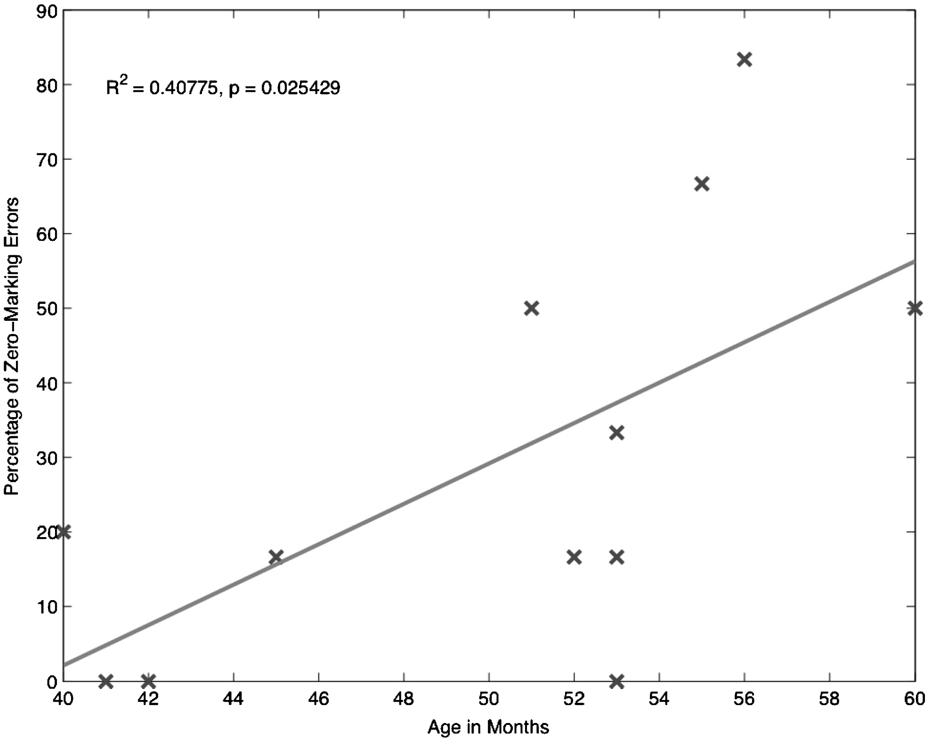

Fig. 7. The relation between age and plural marking errors (zero marking) in Study 1.

been paying attention. The children were told that unfortunately he had not, and were asked if they would come back a couple of days later to teach him again. Each child was tested four times over a 9-day period.

Sessions were conducted in a classroom at the school. They were audiotaped and independently transcribed by two coders who later met to resolve any coding discrepancies.

4.3. Results and discussion

Children's performance across the trials showed a significant increase in adult-like performance (measured as the number of correct forms minus over-regularized forms averaged across each pair of trials) in the last pair of trials ($M_{\text{Trials3\&4}} = 2.2$ out of a possible 6) as compared to the first pair ($M_{\text{Trials1\&2}} = 1.0$ out of a possible 6; $t[9] = 3.213$, $p < .01$; by items, $t[5] = 4.567$, $p < .005$), supporting the idea that children can recover from over-regularization simply by repeatedly activating the appropriate semantic and phonological representations. There was also a significant increase in the number of correct irregular plural forms produced ($M_{\text{Trials1\&2}} = 3.3$, $M_{\text{Trials3\&4}} = 3.9$, $t[9] = 3.086$, $p < .02$) and a concomitant decrease in the number of over-regularized forms produced ($M_{\text{Trials1\&2}} = 2.3$, $M_{\text{Trials3\&4}} = 1.7$, $t[9] = 2.400$, $p < .05$). These results are shown in Fig. 8.

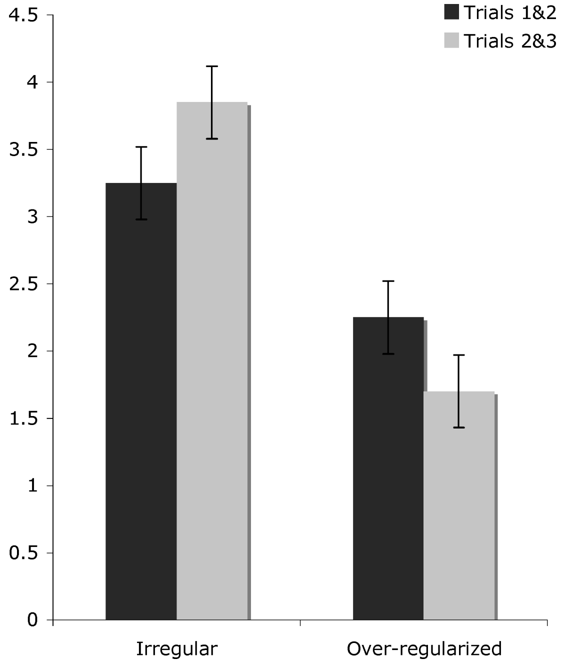

Fig. 8. Forms produced by children in the first and last pairs of trials in Study 2.

5. Study 3

The interpretation of the results of Study 2 is open to two potential objections. First, the children returned home after each trial and may have discussed the trials with their parents, thus receiving corrective feedback in this indirect manner. Second, the children may have heard more irregular forms incidentally in the intervals between tests, thereby receiving more relevant linguistic input by coincidence over the 9 days of the study.

To control for these factors, Study 3 examined a group of 30 children who remained in the laboratory throughout the four training trials, thereby controlling all input to the children throughout the period of testing. In this case, only knowledge acquired prior to entering the laboratory could affect children's responses.

5.1. Participants

The participants were thirty 5- and 6-year-old children (14 boys and 16 girls, average age 6 years, 6 months) recruited from a database of volunteers resident in the vicinity of Palo Alto, California.

5.2. Method

The children again helped a puppet name plural forms for the same six irregular items and the six regular semantic matches. As in Study 2, children were given encouraging feedback irrespective of their output. Children were seated with the experimenter, and in response to pictures presented on a laptop computer, produced first the singular and then the plural forms of each item to "help cookie monster learn the names of things." After each block of items, the children were rested. (They colored pictures for a few minutes prior to the next block, while the puppet "let his head cool down from all that learning.") Each child completed four blocks of trials. All of the blocks were conducted in a single 20-min session during which the children remained in our laboratory.

Testing took place in a dedicated child study laboratory. Trials were videotaped and transcribed independently by two coders, who later met to resolve any coding discrepancies.

5.3. Results and discussion

Three children could not be persuaded to complete four blocks of trials, and the data from 1 child were lost due to a malfunction of our recording equipment. These data, and that of a further 4 children who were at ceiling throughout (they successfully produced all of the irregulars in each block) are not included in the following analyses. Analysis of the remaining children revealed a significant increase in correct performance in the last pair of trials ($M =$ –0.35; performance was measured by taking the number of correct irregular productions and subtracting the number of over-regularized forms produced) as compared to the first pair ($M =$ –0.85), $t(22) = -1.901$, $p < .05$. Significant increases in the number of correct irregular plural forms produced ($M_{\text{Trials1\&2}} = 2.5$, $M_{\text{Trials3\&4}} = 2.8$),$t(22) = 1.780$, $p < .05$, and decreases in the number of over-regularized forms produced ($M_{\text{Trials1\&2}} = 3.4$, $M_{\text{Trials3\&4}} = 3.1$), $t(22) =$ –1.963, $p < .05$, were also observed.

An item analysis did not reveal any significant difference between the earlier and later trials. To examine whether this effect might derive in part from noise introduced by the items FEET and TEETH (in Study 1 we found that these items, which are heavily plural dominant, were often produced by children when singulars were elicited), whose production might not be a reliable indicator of the child's semantic knowledge, we conducted an item analysis excluding FEET and TEETH, which revealed that the improvement in production quality between Trials 1 and 2 and 3 and 4 for the rest of the items was reliable, $t(3) = 2.444$, $p < .05$.

The relation between children's initial performance in the first trials and their gain across trials also offered evidence to support our model's prediction that children who had strong representations of the irregular items on Trials 1 and 2 were more likely to improve, whereas children who demonstrated weak representations of the irregular items on Trials 1 and 2 were at risk of declining performance (see Fig. 9).

To further explore this relationship, we divided the children into two groups, based upon their performance in Trials 1 and 2. Children were assigned to the low ability group if they failed to produce a correct irregular plural or if they only managed to produce one of TEETH or FEET (which are poor indicators of plural semantic knowledge) in the first two trials. Children who produced correct irregular plurals for any of the other items in Trials 1 and 2 were assigned to the high ability group. A 2 (Trial Type: Trials 1 & 2 or Trials 3 & 4) × 3 (Production Type: over-regularized, irregular or zero marked) repeated-measures ANOVA with *production ability* in the first trials as an additional between-subject factor revealed significant interactions between both the earlier and later trials and the type of productions

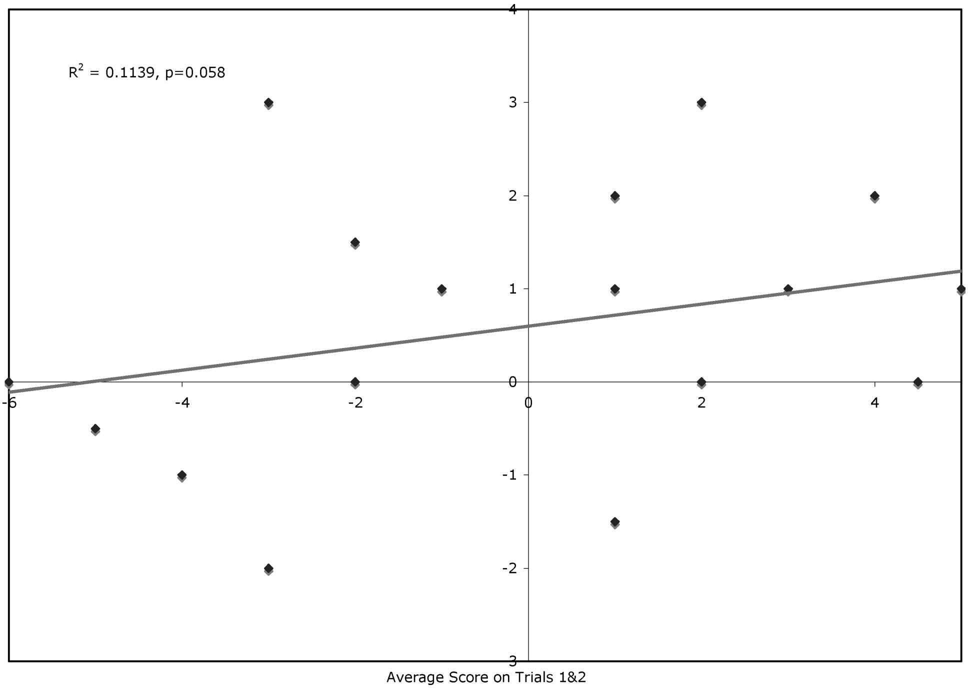

Fig. 9. The relation between initial performance and performance change in Study 3.

children made (Trial Type × Production Type: $F[2, 20] = 25.47$, $p < .0001$) and these factors and children's overall production ability (Trial Type × Production Type × Production Ability: $F[2, 20] = 7.416$, $p < .005$).

A series of separate repeated-measures ANOVAs for each type of production sorted by overall production ability revealed a pattern of data consistent with both the U-Shaped learning prediction of our model, and with the increase in zero marking with increasing competence that we noted in Study 1. The high ability children showed increased irregular production in Trials 3 and 4 as compared to Trials 1 and 2 ($M_{\text{Trials1\&2}} = 3.57$, $M_{\text{Trials3\&4}} = 4.03$), whereas for the low ability children the opposite was true ($M_{\text{Trials1\&2}} = 0.56$, $M_{\text{Trials3\&4}} = 0.38$), the interaction being significant (Trial Type × Production Ability: $F[1, 21] = 6.996$, $p < .02$). The opposite pattern of results held for over-regularization, which declined between the early and late trials in the high ability group ($M_{\text{Trials1\&2}} = 2.33$, $M_{\text{Trials3\&4}} = 1.8$) and increased in the low ability group ($M_{\text{Trials1\&2}} = 5.31$, $M_{\text{Trials3\&4}} = 5.56$; Trial Type × Production Ability: $F[1, 21] = 11.726$, $p < .005$). Finally, as in Study 1, zero marking correlated with irregular performance: Zero marking increased between the early and late trials in the high ability group ($M_{\text{Trials1\&2}} = 1.33$, $M_{\text{Trials3\&4}} = 1.66$) and declined in the low ability group ($M_{\text{Trials1\&2}} = 0.13$, $M_{\text{Trials3\&4}} = 0.06$; Trial Type × Production Ability: $F[1, 21] = 2.803$, $p = .1$).

To ensure that the responses of the experimenters were not providing useful feedback to the children, two naïve raters were presented with the encouraging responses of the experimenters in 20 situations where the child produced a correct irregular form and 20 situations where the child over-regularized, and were asked to guess which were examples of correct experimenter feedback and which were examples of "false positive" feedback. Neither rater performed better than chance (the raters' scores were 47.5% and 50% correct), nor was there any significant correlation between their responses ($r = 0.146$, $p > .3$), suggesting that the feedback that the children were getting was not an obvious source of information concerning the quality of their responses. (It also appeared that the experimenters were succeeding in conveying a positive, encouraging message in their responses—despite being informed that one half of the samples they were hearing represented correct experimenter feedback and one half represented examples of false positive feedback, both raters overestimated the amount of correct feedback, judging 60% of trials to be of this type.)

The children in this study remained in the laboratory throughout testing and received no helpful input, yet they still demonstrated increasingly adult-like performance in their irregular noun plural production over the course of the trials when they received no linguistic feedback.

6. Study 4

To further examine the relationship between the effects of practice and children's development at time of testing, Study 4 examined 10 younger children from the same population (Mary Erskine's School, Edinburgh, Scotland; 5 boys and 5 girls were tested, with a mean age 4 year, 9 months) in the same conditions and using the same procedure as reported in Study 2. We then pooled the data from these children with that collected in Study 2 and divided it into two high and low production-ability groups using the same criteria as in Study 3. The high ability group, who demonstrated some knowledge of irregular plural semantics in Trial 1, again showed improved performance between Trials 1 and 2 ($M = 1.2$) and Trials 3 and 4 ($M = 2.4$). However, in keeping with the predictions of the model, the performance of the children in the low ability group actually declined in the same conditions (see the early decline in irregular performance in Fig. 4; Trials 1 & 2, $M = -1.4$; Trials 3 & 4, $M = -1.9$). As in Study 3, a repeated-measures ANOVA using production ability as a between-subject factor revealed this interaction to be significant, $F(1, 19) = 10.382$, $p < .005$.

7. Study 5

Study 5 was designed to further test our model. We assume that when children are prompted to produce a plural noun by a semantic cue, they reactivate the learned phonological couplets they have come to associate with that cue, and that this leads both to learning and to the spreading activation that results in the over-regularization of irregular nouns at particular stages of learning. The phenomenon of semantic priming (e.g., where priming with the semantics of "doctor" yields shorter response latencies to a lexical decision task on "nurse"; Meyer & Schvaneveldt, 1971) indicates that phonological and orthographic representations can be activated simply by cueing the semantic features (or a significant subset of the features) associated with them.

Our model assumes that until the representation of a phonological–semantic association reaches asymptote, activation of an association will lead to strengthening of its representation.

It follows, therefore, that the effects demonstrated in Studies 2, 3, and 4 ought to be reproducible simply by priming the semantics of the tests nouns, even in the absence of any naming response by the child (semantic-priming effects indicate that the appropriate semantics should activate the phonological representation MICE even when the child does not actually say "mice" or "mouses" for the benefit of the experimenter). Study 5 was designed to test this prediction.

7.1. Participants

The participants were twenty-four 4-year-old children and twenty-four 6-year-old children resident in the vicinity of Palo Alto, California; they were recruited from a database of volunteers (average ages were 4 years, 6 months for the 4-year-olds; and 6 years, 7 months for the 6-year-olds).

7.2. Method

The children were randomly assigned to two groups that were pretested on plural production using the same six irregular nouns, and their regular pairings, as used in the previous studies, and then assigned to one of two conditions. In the experimental condition, the children performed an old/new task in which they were asked to tell a cookie monster whether they had seen things similar to those presented on a computer screen in the pretest. Depictions of the objects were presented on a laptop screen and children were asked to help the cookie monster identify them "by telling him, yes or no?" to indicate whether they had already seen these things. When an object appeared, the experimenter asked the child to "look at those—did cookie monster see those before?" If the children did spontaneously respond they were prompted, "did cookie see these? Yes?? No??" If no response was still forthcoming, the experimenter proceeded to the next item. One half of the items presented were different depictions of the items in the pretest (e.g., a different picture of some mice) and one half were foils. The children were thus tested on 12 new and 12 old items per block.

In the control condition, the children were shown 10 color slides after the pretest and then asked to tell the cookie monster whether they had seen that particular color before in an old/new task that contained an equal number of foils. The colors were presented as blocks that filled the computer screen, to avoid their suggesting any notion of plurality.

The children completed four blocks of the old/new task, and the total time to complete each task (including the initial color presentation in the control task) was equated between conditions. Both sets of children were then posttested on exactly the same set of items and depictions that were used in the pretest.

Testing took place in a dedicated child study laboratory. Trials were videotaped and transcribed independently by two coders, who later met to resolve any coding discrepancies (see Fig. 10).

7.3. Results and discussion

In the experimental condition, the productions of the older children improved significantly in the posttest ($M = 2.9$) as compared to the pretest ($M = 1.4$), $t(9) = 2.913$, $p < .02$; and by

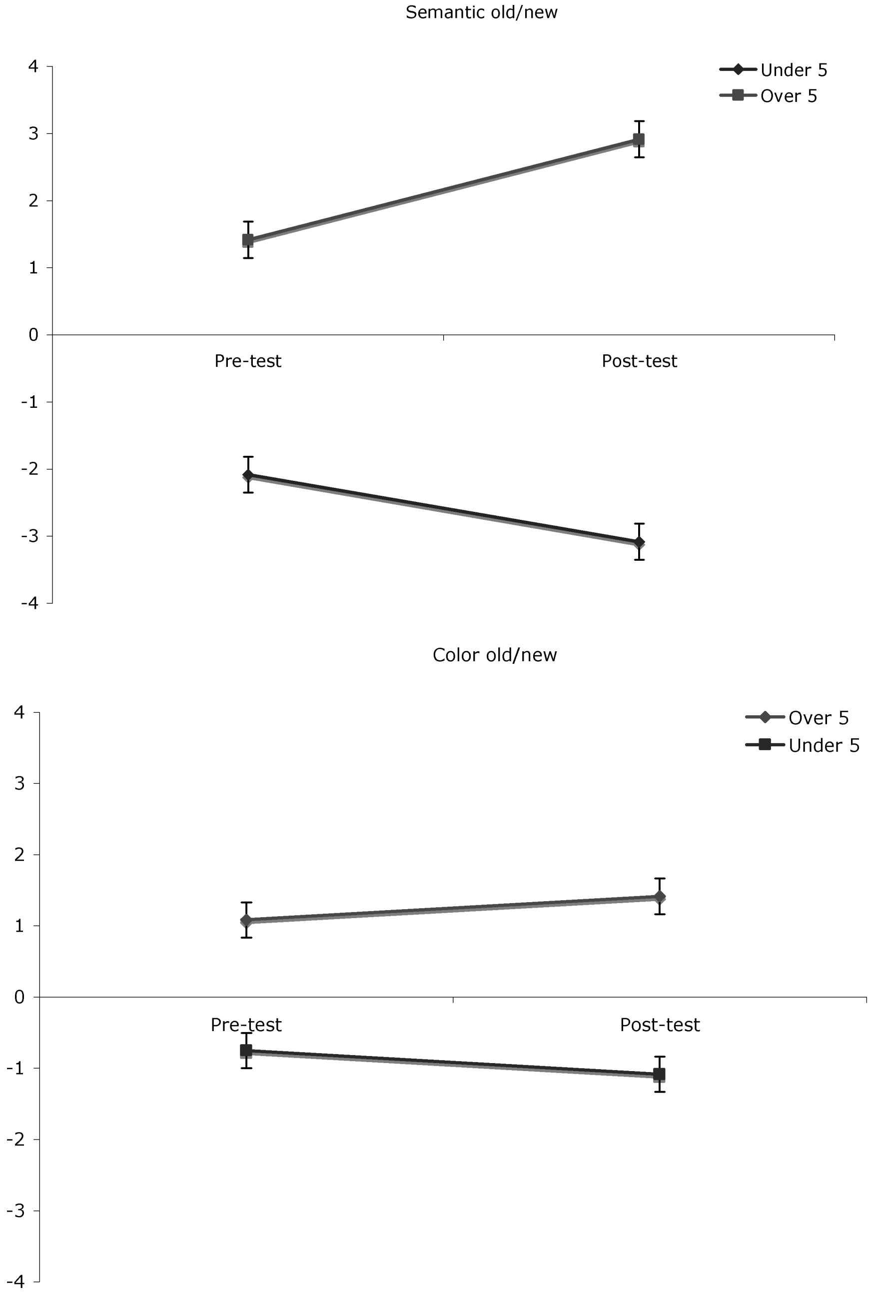

Fig. 10. The performance of children in the control (bottom panel) and experimental (top panel) conditions of Study 5.

items, $t(5) = 2.317$, $p < .1$. However, the exact same training produced exactly the opposite result in the younger children, who performed significantly worse in the posttest ($M = –3$) than in the pretest ($M = –2$), $t(11) = 1.816$, $p < .05$; and by items, $t(5) = 1.870$, $p = .06$. A repeated-measures ANOVA using age as a between-subject factor revealed the interaction between age and quality of irregular production to be significant, $F1(1, 21) = 11$, $p < .005$; and by items, $F2(1, 10) = 6.805$, $p < .05$.

These effects were not present in the control condition, where for both the 6-year-olds and 4-year-olds posttest performance (6-year-olds, $M = 1.4$; 4-year-olds, $M = –1.1$) did not significantly differ from pretest performance (6-year-olds, $M = 1.08$, $t[11] = 0.715$, $p > .2$; 4-year-olds, $M = –0.75$, $t[11] = 0.615$, $p > .2$). Although it was the case that the older children improved slightly between pre- and posttesting, whereas the younger children on average showed a slight decline in performance over the same period (we would expect the pre- and posttests themselves to provide some strengthening of children's representations; see Tulving, 1967), a repeated-measures ANOVA using age as a between-subject factor did not reveal any significant interaction, $F(1, 23) = 0.871$, $p > .3$, suggesting that the extra training trial provided by the posttest was not sufficient to generate these results alone. Finally, an omnibus ANOVA, using both age and condition as between-subject factors revealed that overall there was a significant interaction between age and pre- to posttest performance, $F(1, 44) = 9.3$, $p < .005$; and a marginally significant interaction between age, training type, and pre- to posttest performance, $F(1, 44) = 3.12$, $p < .09$, which is consistent with both the effects that we anticipate will derive from training during testing, and the additional strengthening we predicted would result from exposure to items in the old/new task.

Consistent with the predictions of our model, it appears that priming the semantics of the plurals of the test nouns, even in the absence of any overt naming response by the children, was sufficient to produce learning—in the predicted U-shaped pattern—in the experimental condition. In this regard, these results raise questions for models that assume that the process by which children learn plural inflection involves them comparing their productions to a stored template and updating their representations by means of an error signal (such as the back-propagation models proposed by Plunkett & Juola, 1999; Plunkett & Marchman, 1991, 1993; and Rumelhart & McClelland, 1986). Because the children in Study 5 did not produce the names of the items during the old/new task (rather they generated yes or no responses to indicate to the cookie monster whether he had seen the items in the pretest), it appears that their explicit productions could not be used to generate an error signal. This, of course, raises the question of whether the children subvocalized the names of the items during the task. Although this possibility cannot be conclusively ruled out in the present context, there is evidence that when presented information is in the form of a visual depiction, children do not spontaneously use subvocalization in memory tasks until 7 or 8 years of age (Halliday, Hitch, Lennon, & Pettifer, 1990; Hitch & Halliday, 1983), suggesting that it is unlikely that the children in this experiment subvocalized the names of the items while performing the old/new task or that they used feedback from subvocalization to guide their learning. Clearly, this concern does not count against back-propagation models as proof of concept models when it comes to questions of learnability. However, the changes in behavior manifested by children in this study in the apparent absence of any explicit feedback signal does raise questions about the way that the operations of back-propagation or other error-driven learning algorithms are to be properly conceptualized in this instance.

8. General Discussion

The series of studies we have reported suggest that children's over-regularizations in noun productions may result from competition between the representations of items in a developing memory system and, as such, they provide an alternative to the idea that over-regularization behavior in children provides evidence that they have postulated genuine "superset hypotheses." As long as children have successfully learned representations of the correct forms from experience (as revealed in Study 1), correct production performance can arise in a child who over-regularizes as item representations strengthen in memory through practice and reach a state of learned equilibrium. From this perspective, superset hypotheses are simply transitional states that arise and resolve themselves as the representations underlying probabilistic responses develop. Moreover, children can successfully resolve superset hypotheses simply through repeatedly rehearsing the production of the knowledge they have extracted from the environment. They do not appear to need feedback, explicit or otherwise, to do this. These results are therefore consistent with earlier simulations of the development of inflection in connectionist production networks (Plunkett & Juola, 1999; Plunkett & Marchman, 1991, 1993; Rumelhart & McClelland, 1986) in that they suggest that this particular form of the LPLA does not present an obstacle to the idea that language can be learned. Where the findings here extend on previous work is that they show not only that children may recover from over-regularization errors (and, therefore, superset grammars) without the need for explicit parental feedback (or, indeed, *any* feedback), but that they can and do recover from these errors in this way.

In demonstrating how the internal dynamics of children's developing representational systems create and resolve erroneous over-regularization behaviors, these studies expose the limited relevance of logical arguments about behavior to problems such as the acquisition of language, simply because predictions about the way a child's language will develop can only be made if the various representations it comprises and the ways in which they interact are considered. One simply cannot make predictions about how a given representation will develop over time without considering the other representations in the system and their development over the same period.

The data presented here have been interpreted in terms of a model in which recovery from over-regularization reflects a natural learning process. These data do not, however, show that language is—therefore—*all* learned; nor could they. What they do show is that blanket claims about language learnability, in general, are of limited use to theories of language acquisition. Learnability is contingent on both the architecture of and inputs to a learning system. The extent to which language is learned is an empirical question whose answer lies in the study of the *mechanisms* through which language is acquired and used. What these studies suggest is that insofar as the LPLA has been a problem for linguists and philosophers, it has been so because it disregards the specific mechanisms of learning employed by children and the ways in which these interact over time.

8.1. Child and adult language learners—What differs?

The development of a mechanistic, predictive account of children's morphosyntactic development that is consistent with more general principles of memory and learning provides a good vantage point from which to consider the *differences* between adults and children when it comes to morphosyntax, language, and learning more generally (numerous studies have shown that repeating errors can produce detrimental effects in adult memory that appear to contrast sharply with the improvements observed in the children in these studies; e.g., see Bartlett, 1932).

In a series of elegant and ingenious studies, Newport and colleagues have revealed, in both naturalistic and experimental settings (e.g., Hudson-Kam & Newport, 2005; Johnson & Newport, 1989; Newport & Aslin, 2000; Singleton & Newport, 2004; see also Derks & Paclisanu, 1967), that the patterns of learning exhibited in children's acquisition of morphosyntax are at considerable variance with those of adults. Children tend to maximize, or overmatch, probabilistic language input: If two forms of the same item occur in the input, children tend to adopt the dominant pattern. Adults, on the other hand, tend to probability match, tracking the probabilities with which the alternative forms are used and attempting to reproduce these in their output. Taken together with the model presented above, these findings allow one to begin to outline of an account of how the learning of inflectional morphology changes with maturation—which, in English, is the best documented problem for late learners (see Johnson & Newport, 1989)—that is consistent with what is known more generally about the development of cognitive control (e.g., see Posner, 2005; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005).

In the model presented here, inherent in children's acquisition of the morphosyntactic patterns for their native languages is a period during which, as a result of competition between possible outputs, the forms children utter are not necessarily those they learn or comprehend. In the model, children do not supervise their own learning: Instead, their behavior reflects the relative strength of possible responses open to them, and they generally output the option that is best supported.

The development of control processes in the prefrontal cortex throughout childhood (Davies, Segalowitz, & Gavin, 2004; van Leijenhorst, Crone, & Bunge, 2006; for a review, see Ramscar & Gitcho, 2007) brings online abilities that allow adults to respond to and select between the competing responses supported by their current knowledge (see Botvinick, Braver, Carter, Barch, & Cohen, 2001; Yeung, Botvinic, & Cohen, 2004), and it is possible that some of the maturational changes affecting the learning of inflectional morphology may relate to the changes in learners' ability to detect and respond to conflict between competing morphological forms. In effect, cognitive control may allow adult learners to shortcut the unsupervised learning that characterizes children's learning of their languages (and, hence, native patterns) and, as a result, learn different (non-native) patterns of inflection to those acquired by children (Johnson & Newport, 1989).

Articulating and integrating accounts of the computational and neurological mechanisms by which the architecture of plural learning changes in development along the lines we suggest above, beginning in a largely imitative fashion and developing into a more controlled process over the course of childhood, should eventually yield a better understanding of the maturational changes that occur in language acquisition (Johnson & Newport, 1989). Ultimately, we hope that this process may also allow research in language acquisition to connect with broader theories of cultural and cognitive development (e.g., see Tomasello, 1999). Language is ultimately a cultural capacity (Tomasello, 1999; Wittgenstein, 1953); arguably, it is the capacity for culture that sets *Homo sapiens* apart from our closest neighbors. Understanding how the processes of imitation that appear to be key to the acquisition and establishment of cultural common ground interact with the processes that allow humans to exert more cognitive control over their responses, and thus achieve agency across the course of cognitive development, may ultimately result in a much deeper understanding of our capacity for, and the nature of, both language and culture.

Notes

1. In assuming that the features that trigger plural production are those relating to the situational semantics of plural naming and usage (i.e., naming multiple instances of count-noun objects, and references to these), our model differs from many other memory-based models of inflectional morphology, which assume that the features that serve as the inputs to the production of an inflected form are the features used to represent its uninflected, or "stem," form (e.g., Rumelhart & McClelland, 1986).
2. In all the simulations we report, $\eta = 0.002$, $s = 0.3$, and there were 50 members of the regular family and 1 member of the irregular family (i.e., $|\mathrm{F}_{REG}| = 50$ and $|\mathrm{F}_{IREG}| = 1$).
3. We do not explicitly model here (or test) the way children produce novel forms (their ability to generalize a novel form such as *wug* to the plural *wugs*; Berko, 1958). Our assumption is that these forms are produced in much the same way as over-regularizations: The presence of multiple instances of *wug* activates other plural responses, and in the absence of competition from a previously learned plural form of *wug*, the resultant activation of the +*s*form generalizes to the plural response *wugs*. Detailed modeling of this phenomenon (and more quantitative modeling of the over-regularization phenomena discussed here at the level of individual items) would require the inclusion of far more information than we include (for the sake of simplicity) in the model we present here. In particular, there is evidence that generalization (and, hence, over-regularization) is strongly affected by the phonological properties of forms in memory (children readily generalize *wug* to *wugs* but fail to generalize *niz* to *nizzes*; Berko, 1958) and the distribution of these forms in phonological space. Ignoring this latter factor can make the way low-frequency forms such as the German $+s$ plural generalize in a wide range of contexts seem puzzling (Marcus, Brinkmann, Clahsen, Wiese, & Pinker, 1995). However, as Hahn and Nakisa (2000) noted, relatively low-frequency forms may generalize more readily than more frequent forms if the low-frequency forms are distributed throughout a phonological space while the frequent forms are clustered in particular spatial locations (as appears to be the case in German). From this perspective, the German $+s$plural is applied to onomatopoeic forms and foreign borrowings as a result of the wide distribution of +s items in phonological space and despite their relatively low token frequencies.

Probabilistically, in any instance of generalization, the closest forms to an onomatopoeic item or foreign borrowing will likely belong to the widely distributed but low-frequency $+s$ phonological class as opposed to a higher frequency but more densely clustered class. Hahn and Nakisa showed that this pattern of generalization can be successfully simulated using in an unmodified version of a widely applied model of human categorization and generalization (Nosofsky, 1986), taking standardized representations of German nouns as input.

4. A single family includes nouns with similar subparts, like MAN, WOMAN, FIREMAN, and so on.

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Appendix (With Ewart Thomas)

In this appendix we derive closed-form solutions for the associative strength predicted by the learning curves of our model for irregular and regular noun forms. We then explore how the predicted timecourse of associative strength depends on the parameters of the model and the conditions under which U-shaped learning is predicted by the model.

Irregular forms

As stated in Equation A1, the change in associative strength on a given trial t is given by

$$\Delta a_{i,t} = \eta(1 - a_{i,t})\left(1 + s \sum_{j \in F, j \neq i} a_{j,t}\right). \tag{A1}$$

However, because we assume that each irregular form is phonologically idiosyncratic, F contains no supporting forms, and the summation in Equation A1 is empty. The equation, therefore, reduces to

$$\Delta a_{i,t} = \eta(1 - a_{i,t}), \tag{A2}$$

or, more properly,

$$\Delta a_{i,t} = \eta(1 - a_{i,t})\Delta t \tag{A3}$$

in which we explicitly recognize the arbitrary, short interval of time between trials as Δt. Equation A3 can thus be viewed as the discrete approximation to a differential equation in continuous time:

$$\begin{aligned}&\frac{da_t}{dt} = \eta(1 - a_t)\\ &\Rightarrow \frac{da_t}{1 - a_t} = \eta dt\end{aligned} \tag{A4}$$

in which the dependence on i is omitted for simplicity. On integrating both sides of Equation A4, we find

$$\begin{aligned}&\int \frac{1}{1 - a_t} da_t = \int \eta dt.\\ &\Rightarrow -\ln(1 - a_t) = \eta t + c'\\ &\quad\Rightarrow a_t = 1 - ce^{-\eta t}\end{aligned} \tag{A5}$$

The constant, c, is related to the initial value, a_0, of a_t as follows:

$$\begin{aligned}&1 - a_0 = ce^{-\eta \bullet 0}\\ &\quad\Rightarrow c = 1 - a_0\end{aligned} \tag{A6}$$

Substituting Equation A6 into Equation A5 allows us to find a final solution for a_t, the associative strength at a given point in learning:

$$\begin{aligned}&1 - a_t = (1 - a_0)e^{-\eta t}\\ &\Rightarrow a_t = 1 - (1 - a_0)e^{-\eta t}\end{aligned} \tag{A7}$$

This is the standard exponential learning curve that has had much currency in the history of experimental psychology (e.g., Ebbinghaus, 1913).

Regular forms

Deriving a closed-form solution for the regular associative strength at a particular point in time is a little more complicated because the basic learning equation does not simplify as it did in Equation A2; the summation over forms in the same "family" is no longer empty. However, we can still apply the same basic strategy to solve the equation.

We can rewrite the basic update rule, as stated in Equation A1, in the following way for the regulars (again, suppressing the dependence of a on i for simplicity):

$$\Delta a_t = \eta(1 - a_t)(1 + Sa_t), \tag{A8}$$

where we make the following definition:

$$S \equiv s\left(\left|F_{\text{reg}}\right| - 1\right). \tag{A9}$$

We can make this substitution because we assume that all the regular forms in a family are equally well-learned at a given point in time, and hence all the $a_{j,t}$ in the summation of Equation A1 are equal; if this assumption were violated, for example, to model item-specific effects in learning, then the following derivation would have to be modified. As with the irregulars, we can interpret this delta rule as a discrete approximation to its continuous counterpart:

$$\frac{da}{dt} = \eta(1 - a_t)(1 + Sa_t)$$

$$\Rightarrow \frac{da_t}{(1 - a_t)(1 + Sa_t)} = \eta dt \tag{A10}$$

We now express the integrand on the left-hand side as a partial fraction to carry out the integration:

$$\frac{1}{(1 - a_t)(1 + Sa_t)} = \left(\frac{1}{1 + S}\right)\left(\frac{1}{1 - a_t}\right) + \left(\frac{S}{1 + S}\right)\left(\frac{1}{1 + Sa_t}\right). \tag{A11}$$

This new form of the LHS fraction in Equation A10 can now be integrated. We therefore have, substituting (A11) into (A10),

$$\int \frac{1}{(1 - a_t)(1 + Sa_t)} da_t = \frac{1}{1 + S}\int \frac{1}{1 - a_t} da_t + \frac{S}{1 + S}\int \frac{1}{1 + Sa_t} da_t = \int \eta dt$$

$$\Rightarrow \frac{-1}{1 + S}\ln(1 - a_t) + \frac{S}{1 + S}\frac{\ln(1 + Sa_t)}{S} = \eta t + d$$

$$\Rightarrow \ln\left(\frac{1 + Sa_t}{1 - a_t}\right) = \eta(1 + S)t + d \tag{A12}$$

Now we can examine the initial timestep ($t = 0$) in order to find a value for the constant term d:

$$t = 0 \Rightarrow \ln\left(\frac{1 + Sa_0}{1 - a_0}\right) = d. \tag{A13}$$

Substituting this formula for d back into Equation A12 gives us:

$$\ln\left(\frac{1 + Sa_t}{1 - a_t}\right) = \eta(1 + S)t + \ln\left(\frac{1 + Sa_0}{1 - a_0}\right)$$

$$\Rightarrow \frac{(1 + Sa_t)(1 - a_0)}{(1 - a_t)(1 + Sa_0)} = e^{\eta(1+S)t} \tag{A14}$$

We can now solve Equation A14 for a_t:

$$\frac{1 + Sa_t}{1 - a_t} = \left(\frac{1 + Sa_0}{1 - a_0}\right) e^{\eta(1+S)t}$$

$$\Rightarrow a_t = \frac{\left(\frac{1+Sa_0}{1-a_0}\right) e^{\eta(1+S)t} - 1}{S + \left(\frac{1+Sa_0}{1-a_0}\right) e^{\eta(1+S)t}} \tag{A15}$$

We can see that the associative strength for the regular forms at time t depends on S (which, in turn, depends on the spreading activation parameter, s, and the number of regular nouns in the same phonological family; see Equation A9); the learning rate, η; and the initial state of learning, a_0.

Conditions for U-shaped learning

In order to explore the conditions and manner in which our model predicts U-shaped learning of the irregular noun forms, we used the results derived in the previous sections to explore the response propensity predicted for the irregular items by the model as we varied (a) the spreading activation parameter, s, from 0 to 1; and (b) the number of regular items in the simulation, $|F_{\mathrm{REG}}|$ from 0 to 100. As previously noted, the learning rate, η, was held at a constant value of 0.0025; and we assumed that each irregular item was, phonologically speaking, *sui generis* (i.e., that $|F_{\mathrm{IREG}}| = 1$).

For each parameter pair, the response propensity predicted by the model was calculated using Equations A7 and A15 and then examined to see if a U-shape curve was predicted. We defined U-shaped learning to occur when the response propensity dipped below 0 (indicating that over-regularization was predicted), but ultimately settled at a value greater than 0 (indicating that the propensity to over-regularize was ultimately conquered). We also measured the strength of the U-shaped effect by recording the magnitude of the difference between the minimum and maximum response propensity (these correspond to the greatest tendency to over-regularize and produce the correct form imitatively, respectively). These values are shown plotted in Fig. A1.

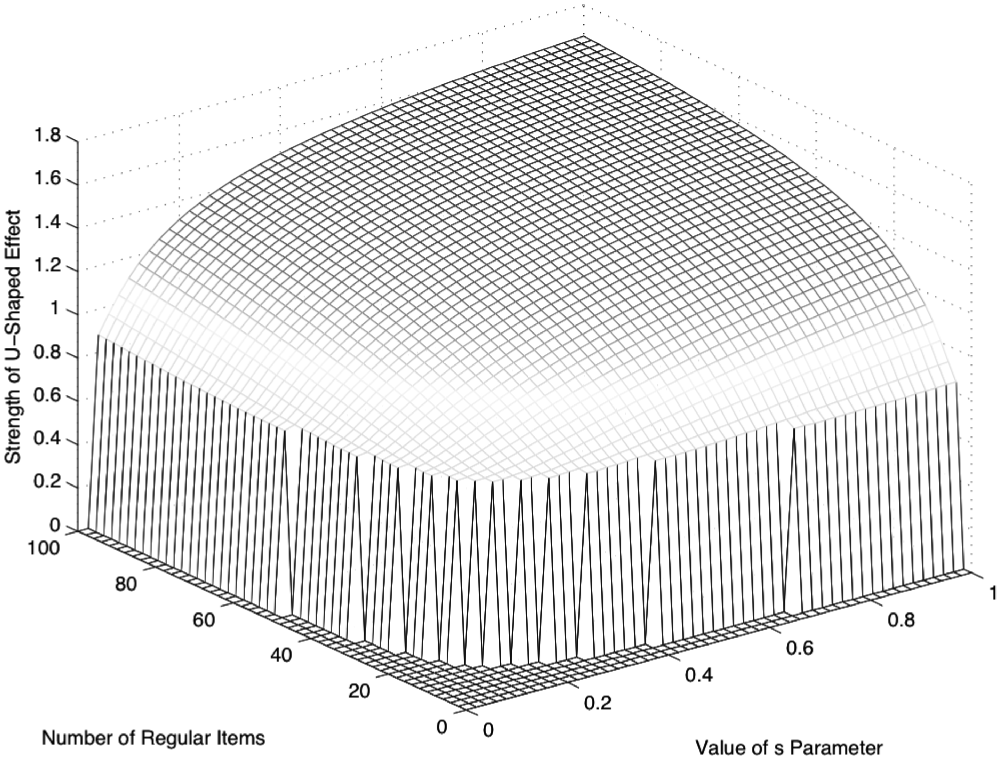

Fig. A1. The magnitude of the U-shaped learning effect for the irregular items as the number of regular items and the spreading activation parameter vary. *Note*: The number of regular noun forms was varied between 0 and 100, and the spreading activation parameter was varied across its full range from 0 to 1.

As can be seen from this plot, a U-shaped learning profile is predicted by the model in almost all circumstances, and is thus not the result of a fortuitous selection of model parameters; and the results of our empirical work thus provide, in some measure, confirmation of the model. Furthermore, as we would expect, the magnitude of the U-shaped effect increases both as a function of the number of regular competing items and the size of the spreading activation parameter.