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When the fly flied and when the fly flew: How semantics affect the processing of inflected verbs

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Although psychological theories of inflectional morphology have traditionally considered phonological and grammatical information to be the only factors affecting inflection, there is ample evidence indicating that semantic information can play a vital role in determining the past-tense forms of homophone verb stems. In this paper, we present two experiments that use on-line measures to test the prediction that semantic context shapes readers' expectations about the past-tense form of an upcoming verb. Consistent with the predictions of "single-route" accounts that model inflection using a uniform process of comparison to stored forms in memory, and contrary to the predictions of theories that posit context-independent rules, semantics are found to strongly influence reaction time data for both irregular and regular verbs, and for both existing and nonce verb forms. At the same time, no dissociation between regular and irregulars is observed, a finding which undercuts "dual-route" arguments for a grammatical constraint on denominal verb inflection. We discuss how these results may be understood in terms of discrimination learning.

Keywords: Semantics; Past-tense inflection; Prediction; Discrimination.

How does the cognitive system mark the past tense of verbs? This seemingly innocuous question—at first blush an obscure and recondite aspect of language processing—has long been at the forefront of a key debate between conflicting theories of language, knowledge-representation, and cognitive processing. This debate focuses on the question of whether the rules of language are real cognitive phenomena, or whether they are epiphenomenal abstractions of mental processes that are implemented in the brain by other means (for reviews see Marslen-Wilson & Tyler, 2005; McClelland & Patterson, 2002; Pinker & Ullman, 2002).

The "mental rules" view is aptly summarised by the correspondence hypothesis (see Miller & Chomsky, 1963), which proposes that rules in mental grammar are used

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directly in language processing. According to this hypothesis, grammatical rules and principles are mentally represented and the language processor operates on mental structures that correspond directly to the structures and operations described in grammar; "the mental parser ... make[s] basically the same distinctions as the grammar" (Clahsen, 1999, p. 995; see also Jackendoff, 1997).

On the flip side of the debate, connectionists and learning theorists posit that linguistic conventions are the product of processes that are neither governed by, nor even necessarily correspond to, the rules put forward by grammarians. In this vein, an array of probabilistic models that do *not* make use of explicitly encoded rules has been put forward to capture the kind of flexible production and comprehension of inflection that humans are capable of (e.g. Daugherty & Seidenberg, 1994; Hahn & Nakisa, 2000; Haskell, MacDonald, & Seidenberg, 2003; MacWhinney & Leinbach, 1991; Plunkett & Marchman, 1993; Ramscar & Dye, 2011; Ramscar & Yarlett, 2007; Westermann, 1998, 2000; see also Baayen & Moscoso Del Prado Martin, 2005; Bybee, 1988, 1995; Bybee & Slobin, 1982; Ernestus & Baayen, 2004; Harm & Seidenberg, 1999; Köpke, 1993; Joanisse & Seidenberg, 2005; Justus, Larsen, de Mornay Davies, & Swick, 2008; Plaut & Booth, 2000). However, these models have been fiercely criticised by advocates of rule-based approaches to inflection. In particular, they have been criticised for failing to ultimately capture the essential nature of inflection, and in particular, *regular* inflection, which is claimed to be explicitly guided by rules (Clahsen, 1999; Clahsen & Felser, 2006; Huang & Pinker, 2010; Marcus, Brinkmann, Clahsen, Wiese, & Pinker, 1995; Prasada & Pinker, 1993; Pinker, 1991, 1999; Pinker & Prince, 1988).

DUAL-ROUTE (OR RULE-BASED) APPROACHES TO INFLECTION

Pinker's (1999) account of inflectional morphology is characteristic of those seen in generative linguistics. He proposes that while the past tenses of irregular forms are memorised by rote, regular forms are generated by a rule, as in the English VERB + *-ed* (e.g. Kiparsky, 1982; but see Anderson, 1992; Halle & Marantz, 1993). This account is problematic on at least two counts: first, it fails to capture the finding that irregular past-tense verbs tend to cluster with other phonologically similar past-tense verbs (e.g., *sing*/*sang, spring*/*sprang, ring*/*rang; stink*/*stank, drink*/*drank, sink*/*sank*) and second, it discounts empirical evidence that novel verb stems can be inflected *irregularly* if they are phonologically analogous to existing irregular verb forms. For example, Bybee and Moder (1983) found that verbs such as *ring*/*rang* and *sing*/*sang* can form the basis for productive analogies that determine the inflection of phonologically similar nonce verbs, such as *spling*/*splang*, and that the more phonologically similar a nonce was to a prototypical pattern among existing irregulars, the more likely it was to be irregularised.

Importantly, irregular nonce generalisation is incompatible with a simple story about rote memory storage and the indexing of a fixed set of memory items (Pinker, 1991, 1999). Accordingly, the dual-route theory of inflectional morphology (Clahsen & Felser, 2006; Marcus et al., 1995; Prasada & Pinker, 1993; Pinker, 1991, 1999, 2001; Pinker & Prince, 1988) modifies the idea of a simple memorised list of irregulars, to include an associative memory component to account for graded irregular productivity. Lexical memory, which stores irregular forms, is supplemented with a component that allows generalisation by phonological analogies to novel verb stems.

Although the dual-route account allows for the analogical processing of irregular verbs, it maintains that an abstract rule is still used to process *regular* verb forms, and

to act as a default in instances when analogical processing in memory fails, or when an irregular form is systematically precluded for grammatical reasons (Pinker & Prince, 1988). Further, the rules put forward in the dual-route account are symbolic: the range of circumstances in which a given rule can be applied need have only the membership of a particular syntactic category ("noun" or "verb") in common. Hence rules are seen as explicit mental mechanisms that can operate on symbolic representations over entire syntactic categories (e.g., in English, the NOUN + *s* rule produces regular plural forms, and the regular past-tense rule is VERB + *ed*). Basing regular forms on a general rule like this is held to account for their extensive productivity: the suffix can be added without regard to the similarities (or otherwise) that hold between the verb-stem to be inflected and any previously encountered regular forms.

SINGLE-ROUTE APPROACHES

Single-route approaches differ from the dual-route account in that they posit a uniform architecture to process inflection. In single-route accounts, memory mechanisms (which even dual-route theorists accept as "uncontroversially needed to capture irregular patterns," Marcus et al., 1995, p. 195) are further used to explain and model patterns of *regular* inflection. Under this approach, both regular and irregular inflections are carried out by analogy to forms stored in memory. This leads to a fundamental difference between the two accounts when it comes to knowledge representation: while the dual-route account involves both memory-based processing (for irregular inflection), and explicit, rule-based symbolic processing (for regular inflection), single-route accounts propose that *all* processing can be accounted for by analogy to stored forms in memory, without requiring the explicit representation of rules.

The homophone problem—what are the inputs to inflection?

In most previous studies—and theories—of past-tense verb inflection, phonological and grammatical information have been considered to be the only relevant factors in the inflection process (e.g. Bybee & Moder, 1983; Clahsen, 1999; Pinker, 1991, 1999; Rumelhart & McClelland, 1986), with the prevailing view being neatly summarised by Pinker (1991, p. 531):

> "Past tense inflection is an isolable subsystem in which grammatical mechanisms can be studied in detail, without complex interactions with the rest of language. It is computed independently of syntax, the subsystem that defines the form of phrases and sentences: The syntax of English forces its speakers to mark tense in every sentence, but no aspect of syntax works differently with regular and irregular verbs. Past tense marking is also insensitive to lexical semantics . . ."

As Pinker and Prince (1988); see also Pinker, 1991, 1999, 2001) have noted, this poses a potentially insuperable problem for the single-route account: how to explain the processing of different patterns of inflection for the same phonological forms in homophone verbs such as *ring*/*wring* and *brake*/*break*? Since *brake* and *break* both sound the same, phonology alone cannot distinguish whether *broke* or *braked* is to be the correct past-tense form for the input breIk; some other information is needed to solve the problem of homophone inflection.

SEMANTICS AND INFLECTION

That information may be semantic: In a series of experiments, Ramscar (2002) demonstrated that the assumption that inflection is driven purely by grammar and phonology is flawed. A series of elicited inflection tasks showed that the semantic context in which a novel verb occurred significantly influenced the forms participants then produced to mark the past tense of that verb. For example, if participants first encountered the novel verb *sprink* in a context involving the consumption of large quantities of vodka and pickled fish (making it semantically similar to *drink*), they were likely to produce an irregular past-tense form for it (*sprank*). But if they first encountered *sprink* in a context describing a disease involving rapid eye movements (making it semantically similar to *blink*), they were likely to produce a regular past-tense form (*sprinked*). A comparison of the forms participants produced for *sprink* in a sparse, "neutral" context (70% irregular) versus those produced in the "rapid eye movement" context (70% regular) provided further evidence that the production of regular past-tense forms increased when the semantic similarity between *sprink* and the regular verb *blink* was increased. These results suggest (1) that semantics may be able to solve the problem of homophone inflection for the single-route approach, and (2) that contrary to a dual-route account, regular forms—not simply irregular forms—can be produced via analogy to semantically similar stored forms (For a replication of these findings, see Gordon & Miozzo, 2008).

SEMANTICS VERSUS GRAMMAR IN HOMOPHONE INFLECTION

The finding that semantics may affect inflection offers a potential solution to the homophone problem: different forms of homophone verbs may be distinguished and computed according to their different meanings. To examine this hypothesis, Ramscar (2002) tested the predictions of a semantic (single-route) account of homophone inflection against those of a dual-route account advanced by Pinker et al. (Kim, Pinker, Prince, & Prasada, 1991; Pinker, 1991, 1999, 2001).

The strong version of the dual-route account predicts that the regularisation of irregular sounding verb stems is driven by innate grammatical sensitivity: any verb that is *perceived* to be denominal (i.e., derived from a noun) will automatically be regularised, meaning that denominal verbs will have different inflection patterns from their irregular "deverbal" verb homophones. While this explanation appears plausible, it has not stood up to scrutiny. Counter-evidence has come from a variety of sources: First, Ramscar (2002) found that participants' sense of the semantic similarities between verb forms correlated strongly with participants' preference for a regular or irregular past-tense form of a homophone verb in context (after partialling out the effects of grammar, $r = .723$), whereas participants' perception of the "grammatical origins" of verbs correlated poorly with their preferences for irregular versus regular past-tense forms (after partialling out semantics, $r = .066$). These findings suggest that semantics not perceived grammatical origin was driving inflection in the experiment.

Complementing these results, Baayen and Moscoso Del Prado Martin (2005) found, in a large-scale corpus study, that while "the probability that a verb is regular increases slightly with increasing noun-to-verb ratio [i.e., increasing likelihood of conversion from noun to verb]" (p. 684), other variables, such as frequency and inflectional entropy, were much better empirical predictors of regularity. Statistically, this implies that whether or not a verb is denominal is actually *less* predictive of its

inflectional patterns than frequency—and certainly, no linguist claims that there is a deterministic relation between frequency and inflection.

ONE OR TWO ROUTES TO INFLECTION?

Findings like these appear to undermine the one "in principle" objection to modeling past-tense inflection using a single mechanism. Pinker et al. (e.g. Huang & Pinker, 2010; Pinker, 1991, 1999, 2001; Pinker & Prince, 1988) have long claimed that the systematic regularisation of verbs based on nouns would require two mechanisms for determining inflections: one method using phonological analogy (to explain cluster effects in inflection, resulting in forms such as *spling/splang*), and another method using grammatical information (i.e., a rule) to explain how verbs based on nouns are automatically regularised. However, the finding that semantics are used to distinguish homophone verbs, and that the perceived grammatical origins of verbs do not determine their past-tense forms, should obviate any *requirement* for models to account for a "grammatically determined" method of inflection.

Since single-route models may be entirely capable of modeling inflection patterns based on phonological and semantic properties (see e.g. Joanisse & Seidenberg, 1999; MacWhinney & Leinbach, 1991; Ramscar & Dye, 2009; Ramscar & Yarlett, 2007), it appears that Rumelhart and McClelland's (1986) claim that single-route accounts provide "a distinct alternative to the view that children learn the rules of English past-tense acquisition in any explicit sense ..." merits further investigation. As Pinker (1991, 1999, 2001) has argued, the peculiarities of the irregular past tense system are best explained by an associative system based on analogy to stored forms, and not by rules; however, if regular and irregular past-tense forms are produced by the same mechanism—based on semantic and phonological analogy—then it may well be that learning the English past tense really does not involve acquiring *any* explicit rules.

The two experiments described in this paper have been designed to further probe this question, while simultaneously addressing some of the criticisms that have been levied at the test design of the original experiments (Ramscar, 2002). Critics of that research have suggested that the subjective measures used in the experiments may have confused or misled participants. For example, Huang and Pinker (2010) contended that "each of the novel words was so similar (both in sound and meaning) to an existing verb, that participants may have *assumed* they were really being asked [to produce] the correct past-tense forms of drink and blink." Similarly, Pinker and Ullman (2003) suggested that:

> the measure of semantic similarity was confounded with headedness: subjects were asked whether the activity described by the target word 'reminded' them of the base word and to 'consider all the possible things they associated with the use of the word.' If two words share a root, one will certainly remind people of the other, and trigger associations with the other. This is distinct from whether the two words share semantic features .... (p. 109)

To address these possibilities, we decided to use an objective, online measure that would preclude these criticisms entirely: reading-time in a true/false lexical decision task. Subjects should be faster to respond to sentences containing past-tense forms that they are anticipating, and slower to respond to sentences containing unexpected forms. By using an objective measure, we can ensure that our findings are not artifacts of a particular testing paradigm, or stem from any subjective confusion on the part of our subjects.

WHAT DOES READING-TIME MEASURE IN THESE EXPERIMENTS?

Recent research has shown that when people are engaged in listening or reading, they build up linguistic expectations about what will be heard or seen next, anticipating upcoming words based on both the structure and semantics of the prior discourse (see e.g., Altmann & Mirković, 2009; Kutas & Federmeier, 2007; Otten & Van Berkum, 2008; Tanenhaus & Brown-Schmidt, 2008; for a brief review of the recent literature, see Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005). In this, people appear to be probabilistically anticipating a number of different words that are likely to follow in a given speech stream or other linguistic frame (Altmann & Mirković, 2009; Ramscar, Matlock, & Dye, 2010; Tanenhaus & Brown-Schmidt, 2008; Wicha, Moreno, & Kutas, 2004). Indeed, there is evidence that given a particular distributional context, readers anticipate upcoming words in a graded fashion that is strongly correlated with their actual likelihood of occurrence within that context (DeLong, Urbach, & Kutas, 2005).

Critically, for our purposes, there is ample evidence to suggest that reading-time is a reliable measure of a word's predictability: numerous studies show that the more predictable a word is in a given context, the faster it will both be read (Ehrlich & Rayner, 1981; McDonald & Shillcock, 2003; Morris, 1994; Morris & Folk, 1998; Schwanenflugel & Shoben, 1985; Traxler & Foss, 2000; Traxler, Seely, Foss, Kaup, & Morris, 2000) and responded to in lexical decision tasks (e.g., Duffy, Henderson, & Morris, 1989; Fischler & Bloom, 1979; Hess, Foss, & Carroll, 1995; Kleiman, 1980; McClelland & O'Regan, 1981; Schwanenflugel & LaCount, 1988; Schwanenflugel & Shoben, 1985; Schwanenflugel & White, 1991). Thus, a reading-time measure will provide us with a concrete indicator of how predictable a particular past-tense form is in a given context: specifically, an expected form should be read more quickly than an unexpected form (see also Ernestus & Baayen, 2004). This will, in turn, allow us to tease apart whether expectation of a particular form is shaped by semantics *or* by the combinatorial operations of the grammar. Will readers expect denominal verbs to always take a regular form, as predicted by the dual-route model (Kim et al., 1991, 1994; Pinker, 1991, 1999)? Or will readers derive their expectations about the verb's inflectional patterns on the basis of the semantic context (Ramscar, 2002; Tabak, Schreuder, & Baayen, 2010; Woollams, Joanisse, & Patterson, 2009)?

DERIVING PREDICTIONS FROM THE SENTENCE PROCESSING LITERATURE

To answer these questions, it is necessary to first establish what dual-route and single-route accounts predict for a lexical decision task. Dual-route theorists subscribe to a modular view of language, which suggests that grammatical processing should be largely insensitive to nongrammatical information sources, such as semantics or pragmatics. While higher-level information may be factored in at later stages of processing, the fundamental claim is that syntactic biases should be readily observable in processing speed, whatever other biases may be present (Ferreira & Henderson, 1990; Forster, 1979; Mitchell, 1987; Rayner, Carlson, & Frazier, 1983). In one of the hallmark papers arguing for this approach, Ferreira and Clifton (1986) reported evidence from eye movement and self paced reading tasks that "syntactic processing biases [are observed] even when they result in thematically based anomaly or when they conflict with discourse biases" (p. 348; but see Trueswell, Tanenhaus, & Garnsey, 1994). Consistent with this, if dual-route theory is correct in claiming that denominal

verbs are automatically regularised by the grammar, then this grammatical "constraint" should be logically prior to semantic biases, which should have little bearing on reaction time data. This would predict, then, that readers should be reliably faster at responding to regular past-tense forms (allowed) than irregular past-tense forms (disallowed), regardless of semantic context.

In contrast, an alternative approach—potentially more consistent with the single-route view—is to claim that multiple interacting constraints influence processing (see e.g., MacDonald, Pearlmutter, & Seidenberg, 1994; McRae, Spivey-Knowlton, & Tanenhaus, 1998; Tyler & Marslen-Wilson, 1977). Notably, the family of lexical-constraint-based competition models is a diverse one. While all of these models share the assumption that multiple information sources are available to guide processing, they differ in how they weight their respective contributions, with some assigning a primary role for semantics, while others downplay its contribution (for recent reviews, see Elman, 2009; Tily, Fedorenko, & Gibson, 2010). Here, we side squarely with the former camp in hypothesising that semantics will strongly bias interpretability. On this view, reaction times should be faster when the form (regular or irregular) is predicted by the semantic context, with no influence of grammaticality.

However, we would also admit a third possibility and potential middle-ground: if a denominal constraint does, indeed, exist, but can be subjected to semantic biases (contra Pinker's claims), then this would predict an interactive effect, in which reaction times should be modulated both by grammatical status and semantic context. The following experiments were designed to test these three possibilities against each other.

EXPERIMENT 1

Experiment 1 was designed to test whether meaning has an effect on the comprehension of past tense verb forms by measuring the reading-times of regular and irregular forms of existing verbs in different semantic contexts. A strong dual-route model of inflectional morphology makes two claims: first, that any verb that is perceived to be denominal will automatically take a regular past-tense form, and second, that the processing of regular past-tense inflection is unaffected by meaning or associative factors in memory:

> [Regular inflection] is modular, independent of real-world meaning, non-associative (unaffected by frequency and similarity) sensitive to abstract formal abstractions (for example, root versus derived, noun versus verb), more sophisticated than the kinds of "rules" that are explicitly taught, developing on a schedule not timed by environmental input, organized by principles that could not have been learned, possibly with a distinct neural substrate and genetic basis. (Pinker, 1991, p. 534; see also Pinker, 1999, 2001)

Accordingly, dual-route theory predicts that readers should expect a regular past-tense form of denominal verbs, regardless of the semantic context in which they were learned about (Kim et al., 1991). This suggests that on any given test trial, regular past-tense forms should be read significantly faster than irregular past-tense forms, which are supposed to be proscribed by the grammar (see Fig. 2 in Pinker & Ullman, 2002).

The contrasting single route prediction tested here was that semantic factors—rather than a default combinatorial "rule"—would bias expectation of inflected forms. This suggests that (1) an irregular past-tense form will be faster read when it occurs in a semantic context where one would expect to find a phonologically identical irregular, whereas (2) a regular past-tense form will be faster read when it occurs in a semantic

context where one would *not* expect to find a phonologically identical irregular. Conversely, reading should be slowed whenever one finds a form in a semantically unpredictable context: for example, a regular form where an irregular was expected, or an irregular form where a regular was expected. Notably, a single route account does not predict any overall processing advantage for regulars. These predictions are in keeping with the findings of Ramscar (2002), Experiments 2, 3, and 4.

Finally, we considered a third alternative: that both semantic and grammatical biases might play a role in biasing processing times (Table 1).

Participants

Thirty-six students at the University of Edinburgh voluntarily took part in this study. All of the participants were native speakers of English.

Materials

Four sets of materials examined four existing verb forms (*sink*, *fly*, *drink,* and *food-drive*).[1] Each verb was presented in one of two contexts. In each context, the verb examined was introduced as a noun (to distinguish its meaning from ordinary uses of the corresponding irregular verb), and then later used as a verb. The contexts in which the verbs were presented were identical apart from a single semantic contextualising sentence (shown in italics in Table 2), which was varied across the contexts to manipulate the degree of semantic similarity between the verb and the ordinary irregular verb from which it was derived (see also Zeelenberg, Pecher, Shiffrin, & Raaijmakers, 2003).

The two contextualising sentences are italicised in Table 2. The first context described an action that was semantically similar to *flying* simpliciter. The second context was semantically dissimilar to *flying* simpliciter. In order to obtain independent confirmation of the predicted semantic similarities, three naive raters were presented with the contexts on cards in randomised order and asked to order the

TABLE 1

A summary of the four experimental conditions. We tested the following hypotheses against each other: (1) A single-route (semantic) account predicts that past-tense verbs presented in semantically congruent contexts will be responded to faster than those presented in semantically incongruent contexts, regardless of grammatical form [**2–3** < **1–4**]. (2) A dual-route (modular) account predicts that past-tense regulars will be responded to faster than past-tense irregulars, regardless of semantic context [**1–3** < **2–4**]. (3) An interactive account predicts that both grammatical form *and* semantic context should have a biasing effect on processing speed [**3** < **2 and 1** < **4**]

Semantic context	*Regular verb form*	*Irregular verb form*
Irregular	Regular verb in Irregular semantic context (**1**)	Irregular verb in irregular semantic context (**2**)
Regular ("Dissimilar to Irregular")	Regular verb in Regular semantic context (**3**)	Irregular verb in Regular semantic context (**4**)

[1] In devising the sample tested here, we took into account the comparative rarity of the lexical population under consideration. In English, there is a limited number of irregular verb clusters, and a correspondingly small number of homophone verb pairs. Indeed, there are likely no more than a handful of cases in which an existing lexical item can be presented in novel noun and verb forms with irregular or regular past tenses. Given that sample sizes should be matched to the size of the sampling population, four items provide a representative sample here.

TABLE 2
Example Contexts (The denominal verb is highlighted)

To promote business, the pesticide shop always stands a man in a giant fly costume at the entrance of their shop, to greet customers. This is especially fun for children. Whenever a child enters the shop, the greeter performs "the fly." *The child sits between the wings on the greeter's back, and they buzz up and down the aisles, ducking and swooping.* In the shop, the term to describe how the greeter greets children in this way is "to fly them." One hot day in June, sweating in his fly costume, I saw the greeter *fly* 40 children in a single afternoon. The look of tiredness on his face was really something.
To promote business, the pesticide shop always stands a man in a giant fly costume at the entrance of their shop, to greet customers. This is especially fun for children. Whenever a child enters the shop, the greeter performs "the fly." *The greeter tells the children jokes and gives out prizes.* In the shop, the term to describe how the greeter greets children in this way is "to fly them." One hot day in June, sweating in his fly costume, I saw the greeter *fly* 40 children in a single afternoon. The look of tiredness on his face was really something.

contexts in each set according to how much the actions described in them matched the action they normally associated with the appropriate irregular verb (*fly*, *drink*, *sink*, and *drive*). The raters concurred with the ordering assigned to the contexts in the experiment, and inter-rater agreement was 100%.

The full set of materials for Experiment 1 is provided in Appendix 1.

Procedure

Participants were told they were taking part in a memory study. Passages were presented on-screen and participants were instructed to memorise them. After memorising a particular passage, participants were asked to indicate whether five sentences relating to the context passage were "True or False" by pressing the appropriate button on a computer keyboard as quickly as they could while concentrating on accuracy. The correct answer to three of these questions was "False" (e.g., in relation to the example in Table 2 participants were asked to state whether "The greeter was dressed as a pig" was true or false). The other two questions checked that participants remembered the noun use of the verb in question (e.g. "The greeter performs 'the Fly'") and also that they remembered the semantic reinforcement sentences in the context. The correct answer to these questions was always "True." The presentation order of these five preliminary questions was randomised.

A final, sixth sentence presented to participants was also true, but it took a fact that had been stated in the initial context in the passive voice, and restated it in the active past tense. This tense took either a regular or irregular form. For example, the statement "One hot day in June, sweating in his fly costume, I saw the greeter fly 40 children . . ." was now restated in an actively voiced manner, for example, "The greeter *flew* 40 children" or "The greeter *flied* 40 children."

The delay in milliseconds between the presentation of this sentence and the onset of participants' responses was recorded.

Each participant was presented with one training item, followed by one context from each of the four sets of stimuli. Each participant completed one from each of the four conditions of the experiment: (**1**) a context describing an action that was semantically similar to that implied by an existing irregular verb, with the verb inflected regularly in the target sentence (e.g. *fly—flied*); (**2**) similar context to irregular/irregularly inflected verb; (**3**) dissimilar context/regularly inflected verb; and (**4**) dissimilar context/irregularly inflected verb.

Results

The mean reading time for each item is given in Table 3. Two unrelated *t*-tests showed that as predicted by **single-route** models the target sentences containing the regular past-tense forms of the verbs were processed markedly slower in semantic contexts that prompted expectation of an irregular (**1**) (mean sentence reading time = 2,461 ms, $SD = 1{,}381$ ms) than in contexts that did not (**3**) ($M = 1{,}622$ ms, $SD = 667$ ms); $t(70) = 3.282$, $p < .001$. Conversely, target sentences containing the irregular past-tense forms were processed more easily in contexts that prompted expectation of an irregular form (**2**) ($M = 1{,}774$ ms, $SD = 1{,}071$ ms), as compared to those that did not (**4**) ($M = 2{,}548$ ms, $SD = 1{,}841$ ms); $t(70) = 2.178$, $p < .02$.

To determine whether semantics might be interacting with a grammatical constraint in biasing response times, we then tested each of the predictions of the **interactive** hypothesis (Table 1): first, that target sentences containing regular forms following "regular" contexts (**3**) ($M = 1{,}622$ m) should be processed faster than irregular past-tense forms following irregular contexts (**2**) ($M = 1{,}774$ ms); and second, that regular past-tense forms following irregular contexts (**1**) ($M = 2{,}461$) should be processed significantly faster than irregular forms following "regular" contexts (**4**) ($M = 2{,}548$ ms). Two unrelated *t*-tests offered little support for this hypothesis, showing no significant difference in processing speed for (**3**) or (**2**), $t(70) = 0.724$, $p > .4$; or for (**1**) or (**4**), $t(70) = 0.226$, $p > .8$.

Two-way repeated measures analyses of variance (ANOVAs) were then conducted on the reaction time data, treating both subjects (F_1) and items (F_2) as random effects. There were no reliable main effects of either Meaning, $F_1(1, 35) = 0.23$, $p > .87$; $F_2(1, 3) = 0.22$, $p > .89$, or Grammaticality (Regular versus Irregular verb types) $F_1(1, 35) = 0.235$, $p = < .63$; $F_2(1, 3) = 0.309$, $p > .6$. The lack of a Meaning main effect indicates that—collapsing over the paragraph contexts in which the verbs were embedded—meaning did not produce a processing bias for the verbs. The lack of a main effect of Grammaticality indicates an analogous absence of bias for regular or irregular verbs forms. Regular forms thus enjoyed neither an overall processing advantage, as predicted by a dual-route account, nor a contextually specific processing advantage, as predicted by an interactive account.

Instead, consistent with a single route account, there was a significant Meaning × Grammaticality interaction: $F_1(1, 35) = 12.911$, $p < .001$; $F_2(1, 3) = 156.978$, $p < .001$. As indicated by Figure 1, the interaction was due to Meaning effects at each level of Grammaticality (Regular versus Irregular verb types).

Notably, there were no significant increases in the error rate (participants answering "false" to statements that were assumed to be true) across all of the test sentences. For

TABLE 3
Mean reading times in milliseconds for the target sentences in Experiment 1

	Semantic context			*Semantic context*	
Regular verb form	*Dissimilar to irregular*	*Irregular*	*Irregular verb form*	*Dissimilar to irregular*	*Irregular*
Drinked	1,642 ms	2,759 ms	Drank	2,084 ms	1,490 ms
Food-drived	1,577 ms	2,435 ms	Food-drove	2,166 ms	1,781 ms
Flied	1,686 ms	2,776 ms	Flew	3,051 ms	2,483 ms
Sinked	1,582 ms	1,873 ms	Sank	2,890 ms	1,342 ms
Mean	1,622 ms **(3)**	2,461 ms **(1)**		2,548 ms **(4)**	1,774 ms **(2)**

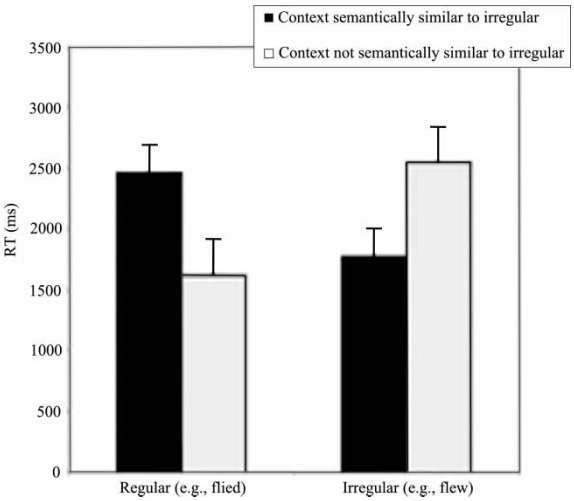

Figure 1. Overall reaction times in Experiment 1.

the true test sentences that were common to each context (the denominal and semantic reinforcement sentences) it was 10.4%. When the semantic context was consistent with the predicted verb tense the error rate for the target sentences was 12.5%; the inconsistent error rate = 9.7%. (The error rates for particular tenses of the target verbs were 12.5% for irregulars and 9.7% for regular.) Further ANOVAs were calculated considering only the "True" responses to the tests sentences containing the target verbs, which again showed no main effects of Meaning, $F_1(1, 35) = 0.138$, $p > .71$; $F_2(1, 3) = 0.000$, or Grammaticality $F_1(1, 3) = 1.131$, $p = .3$; $F_2(1, 3) = 0.519$, $p > .5$, but did show a significant Meaning × Grammaticality interaction: $F_1(1, 35) = 10.635$, $p < .005$; $F_2(1, 3) = 99.047$, $p < .005$.

Discussion

Consistent with previous findings in ratings and elicitation tasks (Ramscar, 2002), the results of Experiment 1 suggest that semantics affect the on-line comprehension of both regular and irregular past-tense forms. Strikingly, the on-line processing of regular forms was significantly affected by semantics: when participants had to read "the greeter *flied* 40 children" in a context where to "do the fly" involved something like ordinary *flying* in a fly-costume, it took longer to process than when "doing the fly" involved telling jokes and giving out prizes clad in the self-same fly outfit. This was despite the fact that the participants' behavioral (true/false) responses were identical in either instance: participants agreed in each case that it was true that "the greeter *flied* 40 children."

These findings are difficult to reconcile with the dual-route claims that the grammar prohibits denominal verbs from taking irregular forms (Kim et al., 1991; Pinker & Ullman, 2002) and that the processing of regularly inflected forms is entirely "independent of real-world meaning" (Pinker, 1991, 1999). Contrary to dual-route predictions, regular past-tense forms did not enjoy an overall processing advantage over irregular forms. Moreover, there was no evidence for even an "interactive" effect, in which both semantic and grammatical biases affected processing speed. In short, there was no evidence for any independent contribution of grammatical form to reaction times.

The interaction between meaning and inflection in this experiment is hardly suggestive of a model in which two independent mechanisms are separately responsible for regular and irregular past tense processing, with one element—the regular—encapsulated and insensitive to the semantic factors that affect the other. Rather, it appears that both regular and irregular past-tense comprehension relies upon a common, semantically and phonologically sensitive process.

DO SEMANTICS AFFECT THE PROCESSING OF NOVEL PAST-TENSE VERB FORMS?

While the results of Experiment 1 provide clear evidence that semantics *do* affect past-tense comprehension, they raise the question of how generalisable these semantic effects are in past tense processing. In Experiment 1, semantic information was necessary to disambiguate between two homophone irregular verbs; however, it may be that the effect revealed in these results stems from some peculiar situation relating to the disambiguation of homophones. For example, it could be that the regular forms of homophone verbs are stored in memory alongside irregular verbs, and thus represent a distinct class of regulars that behave more like irregulars. This raises the question of whether semantic similarity will affect past-tense comprehension when there is no homophone competitor for the inflected verb. It may be that semantics only affect a very few regular verbs that are stored in memory for one reason or another (see Pinker, 1999, for suggestions).

In order to examine whether this was the case, Experiment 2 was designed to examine whether semantics would affect the comprehension of novel verb forms, for which it could be safely assumed that participants did not possess stored past-tense forms.

EXPERIMENT 2

The dual-route account predicts that semantic factors can only affect the comprehension of irregular forms. However, the results of Experiment 1 showed that semantics *did* affect regular comprehension in the case of homophone past-tense forms. In order to ascertain whether this pattern of semantic effects was caused by a particular feature of homophone verbs (which could arguably necessitate storage of regular past-tense forms) or whether it would generalise to other aspects of past-tense comprehension, Experiment 2 examined whether semantics would affect both the regular and irregular forms of nonce verbs for which no past-tense forms were stored.

Ramscar (2002) demonstrated that altering the semantics of nonces such as *frink* to make them similar to existing regulars such as *blink*, or existing irregulars such as *drink*, significantly altered the number of regular and irregular past-tense forms produced in an elicitation task. Making *frink* similar to the irregular verb *drink* led to more irregular production, whereas making *frink* similar to the regular verb *blink* led to more regular production. If semantic similarity does indeed play a role in computing past-tense forms and, in particular, in analyzing them in comprehension, then one would expect that the reading time pattern obtained in Experiment 1 should be similarly observed with novel verbs.

The single-route prediction tested here was that a regular past-tense form should be easier to read when it has been observed in a context of use that is semantically similar to a phonologically similar regular, whereas an irregular past-tense form should be easier to read when it has been observed in a context that is semantically similar to a

phonologically similar irregular. By contrast, the dual-route prediction tested here was that regular past-tense forms should always be easier to read than irregular forms, given that the grammar dictates that all denominal verbs should be regular. Again, we also considered the possibility that there might be an interactive effect of semantics and grammaticality (see Table 1).

Participants

Thirty-six students at the University of Edinburgh voluntarily took part in this study. All of the participants were native speakers of English.

Materials

Four sets of materials examined four nonce verbs (*cleed, frink, freep, clow*). Each nonce was presented in either one of two contexts. In one context, the verb was presented so that its meaning was similar to an existing irregular verb that was phonologically similar to the nonce. In the other context, the verb was presented so that its meaning was similar to a phonologically similar regular verb. For instance, in the irregular context, to *frink* involved the consumption of quantities of vodka and pickled fish, which suggested that it was semantically similar to the irregular verb *drink* (see Table 4; Ramscar, 2002). In the regular context, *frink* was used to describe the symptomatic actions involved with an eye disease, which suggested that it was semantically similar to the irregular verb *blink* (see Table 4).

Three naive raters were presented with the contexts on cards in random order and asked to match the contexts with the target regular and irregular verb by selecting which had the meaning most similar to each target verb (the targets were: *cleed = breed/weed*; *frink = drink/blink*; *freep = sleep/peep*; *clow = throw/mow*). All three raters succeeded in matching all of the contexts with the targets.

The full set of materials for Experiment 2 is provided in Appendix 2.

Procedure

Participants were told they were taking part in a memory study. They were presented with a context passage on a computer screen and asked to memorise it. After memorising the passage, participants were presented with three sentences, which appeared on screen one at a time. Participants had been instructed beforehand to indicate in each instance whether the sentences were "True" or "False" in relation to the paragraph they had just seen by pressing the appropriate button on a computer keyboard. The order of these sentences was randomised.

TABLE 4
Example contexts from Experiment 2 (The nonce verbs are highlighted)

1. Frink is semantically similar to drink. In a traditional spring rite at Moscow University Hospital, the terminally ill patients all ***frink*** in the onset of good weather, consuming vast quantities of vodka and pickled fish. Last year, his favourite vodka glass in hand, I saw cancer patient Ivan Borovich ***frink*** around 35 vodka shots and 50 pickled sprats. It is not recorded whether this helped in his treatment.
2. Frink is semantically similar to blink. In a classical symptom of Howson's syndrome, patients all ***frink*** in their right eye if they are left handed or left eye if right handed, their eyelids opening and closing rapidly and uncontrollably. Last year, while suffering extreme discomfort from his bad eye, I saw Howson's patient Ivan Borovich ***frink*** around 35 times per minute for days, causing severe damage to the muscles in his left eyelid.

One of the first three sentences was always true and reinforced the meaning of the nonce verb introduced in the preceding paragraph: for example, for the sample context in Table 3, this sentence was "At the Moscow hospital the terminally ill patients all *frink* in the onset of good weather." The other two sentences were false in relation to the paragraph.

A final, fourth sentence presented the nonce verb in either its regular (e.g., *frinked*) or irregular (*frank*) past-tense form: for example, for the sample context in Table 3, the sentences "Last year Ivan Borovich *frinked* a lot" and "Last year Ivan Borovich *frank* a lot" were used. The final target sentence was always "True" in relation to the memorised context, and a target sentence pair was used for each regular and irregular context in which only the past-tense form of the nonce was varied.

Since participants would not have seen past-tense forms for any of the novel verbs before, they were instructed to answer the True/False questions "based on the facts, rather than the particular form of words used to express them." This was to try and reduce any effect on participants' behavioral responses in the True/False task due to their unfamiliarity with the forms of words used to describe events in the base contexts.

Each participant was presented with one training item, followed by a context from each of the target pairs, such that each participant completed one from each of the four conditions of the experiment: (**1**) an irregular context with the nonce inflected regularly in the target sentence; (**2**) irregular context/irregularly inflected nonce; (**3**) regular context/regularly inflected nonce; and (**4**) regular context/irregularly inflected nonce (see Table 1). In each instance, the delay in milliseconds between the presentation of the final True/False sentence and the onset of a participant's response was measured.

Results

The mean reading times for all the items is given in Table 5 (two subjects provided responses that were greater than two standard deviations from the mean for the response type, and their data are excluded from these figures). Two unrelated *t*-tests showed that as predicted by **single-route** accounts, the target sentences containing the regular past-tense forms of the nonce verbs were processed faster following semantic contexts that promoted expectation of an existing phonologically similar regular (**3**) (mean sentence reading time = 2,648 ms, $SD = 961$ ms) than following the contexts promoting expectation of a phonologically similar irregular (**1**) ($M = 3{,}044$ ms, $SD = 1{,}078$ ms); $t(66) = 1.869$, $p < .05$. Conversely, the sentences containing irregular past-tense forms were processed more easily following semantic contexts that promoted expectation of an existing phonologically similar irregular (**2**) ($M = 2{,}398$

TABLE 5
Mean reading times in milliseconds for the target sentences in Experiment 2

	Semantic context			*Semantic context*	
Regular verb form	*Regular*	*Irregular*	*Irregular verb form*	*Regular*	*Irregular*
Clowed	2,677 ms	3,188 ms	Clew	2,660 ms	2,271 ms
Preeded	2,177 ms	3,110 ms	Pred	2,872 ms	2,786 ms
Freeped	2,654 ms	3,385 ms	Frept	3,551 ms	2,441 ms
Frinked	3,143 ms	2,587 ms	Frank	3,234 ms	2,143 ms
Mean	2,648 ms (**3**)	3,044 ms (**1**)		3,072 ms (**4**)	2,398 ms (**2**)

ms, $SD = 793$ ms), as opposed to a regular (**4**) ($M = 3{,}072$ ms, $SD = 1{,}194$ ms); $t(66) = 3.139$, $p < .002$.

To determine whether semantics might be interacting with a grammatical constraint in biasing response times, we then tested each of the predictions of the **interactive** hypothesis (Table 1): first, that target sentences containing the regular past-tense form in regular prompted contexts (**3**) ($M = 2{,}648$) should be processed faster than target sentences containing irregular past-tense forms in irregular prompted contexts (**2**) ($M = 2{,}398$); and second, that regular past-tense forms following irregular contexts (**1**) ($M = 3{,}045$) should be processed faster than irregular forms following regular contexts (**4**) ($M = 3{,}071$). Two unrelated *t*-tests offered little support for this hypothesis, showing no significant difference in processing speed for (**3**) or (**2**), $t(66) = 1.169$, $p > .25$, or for (**1**) or (**4**), $t(66) = 0.098$, $p > .9$.

Two-way repeated measures analyses of variance (ANOVAs) were then conducted on the reaction time data, treating both subjects (F_1) and items (F_2) as random effects. As in Experiment 1, there were no reliable main effects of either Meaning, $F_1(1, 33) = 1.130$, $p > .25$; $F_2(1, 3) = 0.292$, $p > .6$, or Grammaticality $F_1(1, 33) = 0.846$, $p = < .35$; $F_2(1, 3) = 0.736$, $p > .45$. The lack of a Meaning main effect indicates that—collapsing over the paragraph contexts in which the verbs were embedded—meaning did not produce a processing bias for the verbs. Similarly, the lack of a main effect of Grammaticality indicates an analogous absence of overall bias for regular or irregular verbs forms. Here again, regular forms enjoyed neither an overall processing advantage, as predicted by a dual-route account, nor a contextually specific processing advantage, as predicted by an interactive account.

Instead, consistent with a single route account, there was a significant interaction of Meaning × Grammaticality: $F_1(1, 33) = 21.459$, $p < .0001$; $F_2(1, 3) = 14.230$, $p < .05$. As indicated by Figure 2, the interaction was due to Meaning effects at each level of Grammaticality.

The nature of the task in the experiment—which involved making judgments about novel past-tense forms—invariably renders any definition of the "correct" response to the True/False less certain than in Experiment 1. While participants were instructed to answer only on the basis of the facts, it is likely that they were distracted by the novelty of the words. Unsurprisingly then, the "error rate" was somewhat higher than that seen in Experiment 1: For the true test sentences that were common to each context (the denominal and semantic reinforcement sentences) it was 18.4%. When the semantic context was consistent with the predicted verb tense, the error rate for the target sentences was 17.6%; the inconsistent error rate = 20.6%. (The error rates for particular tenses of the target verbs were 23.5% for regulars and 14.7% for irregulars.) Further, ANOVAs conducted on the data with all of the "False" responses, however, removed confirmed the overall pattern: again there were no reliable main effects of either Meaning, $F_1(1, 12) = 2.568$, $p > .12$; $F_2(1, 3) = 0.570$, $p > .5$, or Grammaticality, $F_1(1, 12) = 2.75$, $p = < .12$; $F_2(1, 3) = .012$, $p > .9$, but there *was* a significant interaction of Meaning × Grammaticality: $F_1(1, 12) = 6.406$, $p < .05$; $F_2(1, 3) = 37.415$, $p < .01$. As indicated by Figure 2, the interaction was due to Meaning effects at each level of Grammaticality (Regular versus Irregular verb types). [Finally, the figures for the data including the two participants excluded from the above analysis were also consistent with the corrected data: Meaning, $F_1(1, 35) = 1.035$, $p > .3$; $F_2(1, 3) = 0.334$, $p > .6$; Grammaticality $F_1(1, 35) = 0.186$, $p = < .66$; $F_2(1, 3) = 0.077$, $p > .75$; Meaning × Grammaticality: $F_1(1, 35) = 14.930$, $p < .0001$; $F_2(1, 3) = 22.449$, $p < .02$]

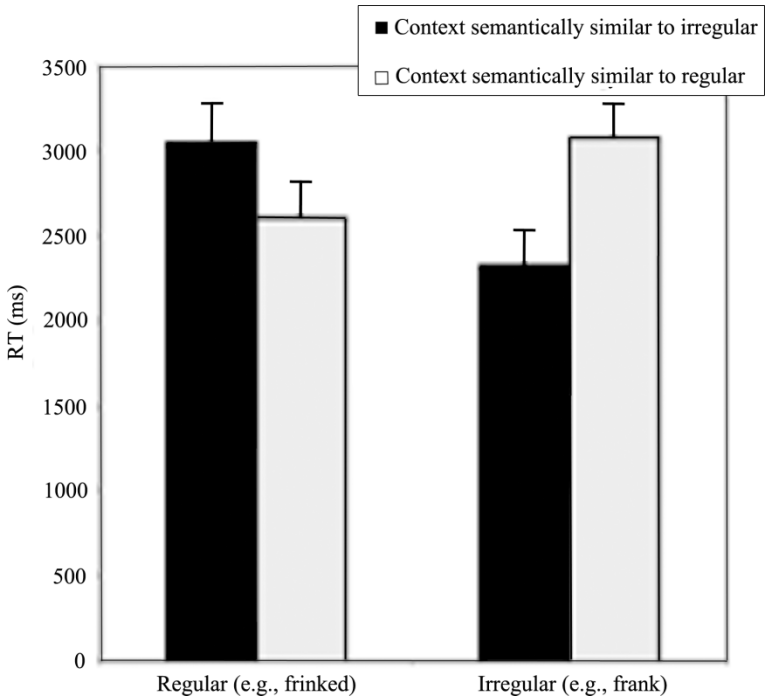

Figure 2. Overall reaction times in Experiment 2.

Discussion

Consistent with the findings of Experiment 1, these results indicate that semantics *do* affect the on-line comprehension of regular and irregular past-tense forms. In particular, it is striking that, once again, there was no processing advantage for regular past-tense forms. Indeed, contrary to the predictions of the dual-route theory of inflectional morphology—which claims that denominal regularisation is grammatically obligatory and that the processing of regular past-tense inflections "is modular [and] independent of real-world meaning," (Pinker, 1991) – participants read irregular past-tense forms significantly faster than regular forms in contexts that were semantically similar to a phonologically similar irregular verb. Moreover, here again, there was no significant difference in processing speed between regular and irregular forms across similarly biased contexts.

The fact that these were nonce forms (i.e., verbs for which participants had never encountered past-tense forms before) is particularly salient. Participants could not have been using verb semantics simply to assist in looking up prestored past-tense forms for these verbs. Rather, it appears that semantics were directly affecting the process by which these past-tense forms were comprehended.

Response latencies as a window into automatic processing

In reading time experiments, lexical decision tasks are widely used to verify that the subject is attending to the content of what they are reading, as opposed to merely running their eyes over the words. They thus serve as a reliable marker of both comprehension and reading speed, and can provide a window into automatic processing. However, there are drawbacks to any testing paradigm (Haberlandt,

1994), and it is thus useful to consider how the RTs reported here compare to those found in other studies, and other testing paradigms.

In both Experiments 1 and 2, participants were asked to respond "true" or "false" to sentences presented on-screen. In each of these instances, we recorded the delay in milliseconds between the presentation of the sentence and the onset of participants' responses. In Experiment 1, the mean number of characters and spaces each participant had to read was 30. Assuming that participants had to scan to the beginning of the sentence when it was first presented, we can estimate that each participant required around 4–5 fixations-and-saccades to read each sentence, with each fixation-and-saccade taking about 200–250 ms (Rayner, 1999). Adding in a usual regression rate of 10–15% produces a reading time estimate of around 1,200–1,300 ms, after which participants would have to judge whether the content of the sentence was true or false and press the appropriate key. Consistent with this, the mean response times were 1,622 ms in the regular consistent condition and 1,774 ms in the irregular consistent condition, suggesting that participants were taking approximately 300–500 ms to consider whether the sentence was true or false, and to generate and execute the key press. Notably, in the inconsistent conditions, participants averaged 2,461 ms (regular) and 2,548 ms (irregular), suggesting cumulative processing delays of roughly 800 ms. An analysis of Experiment 2 yields similar estimates by condition.

The latencies observed are thus compatible with what one would expect to see in self-paced reading (see Just, Carpenter, & Wooley, 1982; Ni, Crain, & Shankweiler, 1996), suggesting that using a different paradigm for assessing reading times would have been unlikely to produce qualitatively different results. Accordingly, it seems reasonable to assume that the RT differences we observed across conditions result from the influence of our semantic manipulations on the automatic processing of the inflected forms.

SUMMARY OF FINDINGS

In Experiment 1, participants were given explicit semantic information about a familiar word, which made that word either semantically similar or semantically dissimilar to an irregular homophone. They then read the word in a new context in a past-tense form, and had their response latencies recorded. From the perspective of expectation, the reaction time measure indicates that participants' reading was slowed whenever they encountered a past-tense form not predicted by the prior semantic context. For example, if the semantics suggested that the word meant the same thing as the common irregular (e.g., "to fly" means to buzz and swoop about, as in "to fly like an insect"), then reading was slowed whenever participants saw an (unexpected) regularised version of the past tense (e.g., "he flied them"). However, if the semantics suggested that the word did *not* mean the same thing as the common irregular (e.g., "to fly" means to tell jokes), then reading was not delayed in this way. This suggests that participants were using their knowledge of the words' semantics to predict their past-tense forms, and that incorrect predictions (e.g., expecting "flew" and seeing "flied" instead) led to reaction time delays.

In Experiment 2, participants learned about the semantics of novel words within context. In this case, they were not given explicit semantic information about these words and were left to predict them from the content and distributional information within the paragraph contexts (see also McDonald & Ramscar, 2001; Zeelenberg et al., 2003). Again, the same reaction time measure indicates that when the past-tense

form was unpredicted by the semantics of the prior context, this manifested in longer response latencies.

Notably, all of the results reported here are significant both by subjects and by items (Clark, 1973). Thus, our findings offer strong support for a single-route semantic account of how inflection is learned and processed. Conversely, the predictions of dual-route theory were not supported by the data from either experiment. Modular accounts of sentence processing make clear that grammatical constraints should be observable even if contrary semantic or pragmatic biases are also present (c.f. Ferreira & Clifton, 1986), and denominal regularisation is supposed to be just such a constraint (Kim et al., 1991, 1994; Pinker & Ullman, 2002). Thus, dual-route theory predicts that, overall, regular past-tense forms should enjoy a comparative processing advantage over irregular forms, which are not predicted by the grammar. Contrary to this prediction, however, there was no main effect of grammaticality in either experiment, indicating that regulars were not processed faster overall. Moreover, on trials in which the semantic context biased an irregular form, reaction times for regular forms were actually significantly *slower* than irregular forms. Thus, there was no evidence of an overriding grammatical bias that might be moderated by semantic biases. Indeed, there was no evidence of even a weak syntactic bias, as might have been predicted by an interactive account.

Weak dual-route accounts

It is hard to square our results with the predictions of dual-route theory. By most accounts, the denominalisation "rule" is not supposed to be a fragile mechanism, observed only in the most carefully controlled experimental conditions; rather, it is claimed to be a robust consequence of the grammar, which is unresponsive to the influence of semantics or context, and which should be readily observable across experimental settings (Pinker, 1999; Pinker & Ullman, 2002). Indeed, a straightforward articulation of the theory holds that in denominal verb inflection, regularisation is obligatory (Pinker & Ullman, 2002), a position which would suggest that biasing the semantic context in which the verb is learned about should have *no* effect on its expected inflection. As Pinker claims, "a word's meaning may be stretched to a wispy filament ... and people will still inflect it as if nothing happened" (1999, p. 186). This claim was, of course, flatly contradicted by our data across both experiments. However, it is worth considering how proponents of this view have (at times) scaled back their claims in accounting for exceptions to this process of "systematic regularisation," to see if a modified dual-route account might be consistent with our findings.

Kim et al. (1991) provide an illustrative example. They contend that in instances in which a denominal verb ends in a verb root that can take irregular inflections—such as green*light* (Liberman, 2007)—the derivation of the verb becomes ambiguous: it could be derived either from the compound noun (suggesting the regular past, greenlight*ed*) or from the irregular verb ending (suggesting the irregular past, green*lit*). In cases such as this, they argue, the imperative to regularise can be bypassed, making the inflectional form the verb takes optional. Presumably, this argument from "derivational ambiguity" could be used to explain the existence of a host of other counterexamples (such as sub*let*, broad*cast*, un*sprung* mass, and test*drive*).

To account for our data, however, the argument from ambiguity would need to be extended to include *any* denominal verb with an ending that could take an irregular

inflection (such as *drink* or *fly* or *frink*).[2] It would also need to provide a principled account for why our experiment—which was specifically designed to bias a denominal interpretation—failed to do so. Assuming that such a position were to be taken, this weakened dual-route account could, in principle, provide an explanatory alternative to our own. A dual-route theorist could argue, for instance, that our readers were simply unable to assess the derivation of our experimental items, which allowed them to bypass the denominal imperative. This would mean, of course, that semantics were free to effectively bias which inflection was expected, just as our results indicated they did.

Unfortunately, while this type of explanatory flexibility may be an appealing means of capturing the relevant data, posing such a broad caveat would be deeply problematic for the broader theory. There are several reasons to think this. First, there would no longer be any means of effectively distinguishing dual-route theory from a discriminative learning account, in which speakers and listeners predict the form of novel productions on the basis of patterns learned from the input. Given that the vast majority of English verbs take regular endings, a learning account predicts that speakers should automatically generalise *-ed* endings to denominal verbs, *unless* the verb ending is phonologically similar to a known irregular (see also Bybee & Moder, 1983). In that case, the verb will also prompt expectation of an irregular inflection, the strength of which will be mediated by semantic factors. This is nearly identical to what would be predicted by a weak dual-route account, but is noticeably absent the commitment to "representational devices committed to grammatical distinctions" (Kim et al., 1991, p. 177). Given that dual-route accounts were initially proposed to capture data that single-route accounts (apparently) could not, this presents a problem. By backing off a purely grammar-driven view of denominal regularisation, dual-route theory would become both (a) largely untestable (it is unclear how the operation of a categorical rule can be established when it can be routinely bypassed), and (b) virtually isomorphic with competing theories with very different theoretical commitments.

This is not even the most serious problem, however. Adopting a weak account would force dual-route advocates to call into question one of the core premises of the approach: that speakers can intuitively distinguish noun–verb pairs in which the verbs are denominal from those in which the nouns are deverbal, and that grammatical constraints (or no) follow in kind. This linguistic analysis is supposed to hinge on which member of the noun–verb pair is more *basic*, which translates roughly to: "which is harder to define in terms of the other?"[3] Ignoring for a moment how underspecified this derivational detection theory is, it is at cross-purposes with the argument from ambiguity, which would suggest that speakers simply cannot intuit the derivations of verbs (or verb roots) that can take an irregular inflection. (Taken to its logical conclusion, this would render ambiguous every irregular verb with a semantic noun complement, such as shoe (*shod*), string (*strung*), drink (*drank*), feed (*fed*), tear (*tore*), sting (*stung*), break (*broke*), spit (*spat*), shot (*shoot*), read (*read*), mistake (*mistook*), overthrow (*overthrew*), etc.). This would then present a fresh problem:

[2] Such a stance would almost certainly be problematic for dual-route theorists, as it directly contradicts the claim that "denominal verbs ... have regular past tense forms, even if homophonous with, or ultimately derived from, an irregular verb" (Kim et al., 1991, p. 179).

[3] "Intuitions of which member of a noun/verb pair is basic presumably involve the semantics of the noun/verb distinction, such as the distinction between entities on the one hand and events or states on the other. For example, "an easy read" can plausibly be thought of as meaning something that is easy for people to read, but "to read the book" cannot easily be thought of as having been derived from the noun read." (Kim et al., 1991)

how are the inflectional patterns of these verbs to be explained if speakers are unable to intuit their grammatical origins?

In short, the argument from ambiguity is unacceptable; it leaves far more to be explained than it answers. Given this, it is not clear how dual-route theory could account for our data, even if a significantly weaker version of the theory was proposed.

DISCRIMINATION-LEARNING AND THE SINGLE-ROUTE APPROACH

> The past tense form of a verb does not directly depend in any way on recurring semantic distinctions. For example, consider the verbs *slap, hit*, and *strike*. They are similar in meaning, but they have different past tense forms: *Slap* has the regular past tense form *slapped*, *hit* has the no-change irregular past tense form *hit*, and *strike* has the irregular past tense form *struck*. Thus, similarity of meaning does not imply similarity of form. Conversely, phonological clusters of irregular past tense verbs are not semantically cohesive: Similarity of form does not imply similarity of meaning, either. Consider the *sting/stung* class of irregular past tense verbs: *sting, sing, drink, shrink, swing, sling, spring, stink, ring*. There is no set of semantic features that seems to distinguish these verbs from those that take different past tense forms, nor is there a set of semantic features that partitions this set of verbs into those that have a past tense form that changes the vowel to an a and those that change the vowel to an U. Semantic features would not help in learning these distinctions; they would just get in the way. (Kim et al., 1991, p. 178)

The results of our experiments here (and the findings of Bybee & Slobin, 1982; Ramscar, 2002) suggest that semantics play an integral role in determining which past-tense form is expected in a given context. How to reconcile this with Kim et al.'s claim that semantic similarity is not tightly coupled with phonological similarity, and vice versa?

First, it is worth touching on work done by Baayen and Moscoso Del Prado Martin (2005), which thoroughly and meticulously examined the merits of Kim et al.'s claim, from the vantage point of lexical statistics. The pair set out to determine whether there were systematic semantic differences between regular and irregular verbs, and concluded that there is "a conspiracy of subtle probabilistic (graded) semantic distributional properties that lead to irregulars having somewhat different semantic properties compared to regulars" (p. 669). Specifically, they found that irregular verbs tend to have more meanings than regulars (i.e., greater "semantic density") and that irregular verbs tend to cluster in semantic neighborhoods (i.e., a higher proportion of their closest synonyms tend to also be irregular). They also found that this occurs on a graded scale, with large subclasses of irregulars behaving more like regulars, as compared to smaller, more idiosyncratic subclasses.

With these results to hand, Baayen and Moscoso Del Prado Martin found that a wide range of empirical findings suggesting "dissociations" between regulars and irregulars could be accounted for in terms of their respective distributional and semantic properties, without recourse to any putative grammatical rule. (Their analysis ranged from studies involving association norms and word-naming latencies, to those involving familiarity ratings and neuroimaging.) The force of their work is clear: contrary to Kim et al.'s claim, meaning and form *are* interrelated, if perhaps not in any simple, collapsible, or deterministic manner. As Huang and Pinker

acknowledge, their findings are "consistent with the [general] idea that people tend to generalize inflectional patterns among verbs with similar meanings."

While this certainly undermines one of the major premises of the dual-route approach, Kim and colleagues' critique of connectionist models may still be a valid one. If meaning and form are subtly—rather than deterministically—coupled, how can psychologically plausible models represent these relations without over-generalising? In other words, how to differentiate between *ring-rung* and *wring-wrang* on the basis of semantics, while not over-generalising semantics in the case of *hit-hit* and *strike-struck*? Or similarly, how to extend the inflection of *sing-sang* to *spring-sprang* and *ring-rang*, while not over-generalising the pattern to *bring-brought* or *fling-flung*?

The solution, we suggest, lies in how one models learning: as a top-down process of similarity-based generalisation (see Goldstone & Son, 2005; Hahn & Ramscar, 2001; Murphy, 2002 for reviews) or as a bottom-up process of discrimination (Baayen, Milin, Filipovic Durdevic, Hendrix, & Marelli, 2011; Ramscar, Yarlett, Dye, Denny, & Thorpe, 2010). Formal learning models are bottom-up in approach, and suggest that applying the phonological and distributional patterns of one word to another—as our subjects appeared to—is not so much a productive inference, as an *over*generalisation, which indicates a lack of discrimination. On this view, generalisation is the default; discrimination (and differentiation) is what transpires over the course of learning. This suggests that the similarity relationship between two or more words is a function of how much learning has *discriminated* those words from each other: the less discriminated, the more similar they appear; the better discriminated, the less similar, and the more distinctly understood their meanings and patterns of use (for an extensive discussion of this approach, see Ramscar et al., 2010).

This learning trajectory—of over-generalisation giving way to more precise understanding—is readily apparent in linguistic development. Childhood speech is rife with examples: for instance, young children tend to initially apply the word "dog" indiscriminately, calling many animals—such as cats and bears—"dogs" (Rescorla, 1980, 1981), prior to discriminating dogs' peculiar semantic cues from that of other animals; likewise, they use number words like "two" and "four" and color words like "blue" and "yellow" interchangeably before discriminating them from one another (Rice, 1980; Wynn, 1992). In a similar vein, there is a tendency among children to over-regularise the phonological patterns of irregular nouns and irregular verbs, saying "mouses," for instance, instead of "mice," "brang" instead of "brought," and "maked" instead of "made" (Marcus, 1996).[4]

In adult speech, learning of novel words may follow a similar pattern: for example, take a young essayist who substitutes a newly learned word in an inappropriate context. Her teacher may chide her with a comment like "this word doesn't quite have the right connotation here." This can be seen as another way of saying that the student has not yet differentiated the word's appropriate contexts of use—and in another

[4] A discriminative learning account can make sense of many of the findings in early childhood language development. For instance, in the case of irregular plurals, the tendency for children to over-regularise can be modeled as a lack of semantic discrimination between plural nouns, which initially leads to strong expectation for a regular phonological form, but eventually resolves over the course of discrimination learning (see e.g., Ramscar & Dye, 2009; Ramscar & Yarlett, 2007). Similarly, a learning model can account for why nouns and verbs "with greater irregular cluster strength (as measured by the number and frequency of similar neighbors) [are] less prone to overregularisation" (Marcus, 1996, p. 82); in a discrimination network, phonological clusters (groups that take the same irregular ending) should be discriminated significantly faster than single idiosyncratic items, resulting in reduced rates of overregularisation.

sense, its peculiar meaning—from a close semantic neighbor (see Riordan & Jones, 2011; Yarlett, 2008).

Kim et al. (1991) have raised the worry that in a connectionist model, "semantic features would not help in learning [phonological] distinctions; they would just get in the way." However, this is only the case so long as the problem is set up as one of learning to generalise: in which case, a model would have to account for (and also provide a psychologically plausible means of correcting for) semantic over-generalisation. However, if learning is seen as a process of increasing discrimination, not generalisation, then this ceases to be an issue: over-generalisation resolves over time as the result of error-driven discrimination learning, which is responsive to the weight of evidence in language and the environment (Ramscar et al., 2010).

Framing the problem, in this way, suggests a novel way of looking at how we learn about words from familiar distributional contexts (as seen in the experiments above and in Ramscar, 2002): First, (1) when one hears a new word—or a new use of a well-worn word—in a familiar context, one's understanding of what that word means, and how to use it, is narrowed based on expectations for which other words might have filled that window. Those expectations may be governed by any number of factors including: the probability of other words given that distributional context; semantic cues in the larger discourse or in the surrounding environment; and even the sound of the word itself (McDonald & Ramscar, 2001; Ramscar et al., 2010; Yarlett, 2008). When one then goes to *use* the new word (2), that word will initially appear quite similar to the word (or words) in the semantic search space learned about in (1). Thus, until future learning discriminates the more nuanced meaning and precise usage patterns of that word, one will use it near "synonymously" (both phonologically and distributionally) to its better learned near neighbors in semantic space. Crucially (3), subsequent learning will begin the discrimination process (Ramscar & Dye, 2009; Ramscar, Dye, Popick, & O'Donnell-McCarthy, 2011): that is, the more one hears the novel word used in ways that distinguish it from its neighbors, the more one will indeed learn to use it (and understand it) separately (see also Arnon & Ramscar, 2011; Baayen et al., 2011).

Under this account, it is not the case that simply because two words are semantically or phonologically related, their inflectional patterns will be identical—far from it. Rather, it is only in the *absence* of learning to discriminate the specific usage patterns (either contextual or inflectional) of a given word, that a novel word will be used in ways that are highly similar to its closest known semantic neighbor, particularly when that neighbor shares phonological characteristics. Thus, the worry that Kim et al. raise is not a concern for any single-route approach that models learning in this way (see also Stemberger, 2002, 2004).

GENERAL DISCUSSION

For more than two decades, the question of how inflectional morphology is processed has served as a battleground for conflicting theories of language, knowledge representation, and cognitive processing. On one side of the debate have been similarity-based or single-route approaches that propose that all past tenses are formed simply through phonological and semantic analogies to existing past tenses stored in memory. On the other side of the debate are rule-based or dual-route approaches that agree that phonological analogy is important for producing irregular

past tenses, but at the same time argue that regular inflection can *only* be explained in terms of symbolic processing.

Ramscar (2002) showed that the one "in principle" objection *against* single-route accounts of inflection—that homophone verbs based on nouns are processed on the basis of their grammatical origins, and not according to their phonological properties—is empirically unjustified: grammatical origin does not predict the past-tense form of verbs, whereas phonology and semantics do. This paper has taken one of the strong claims *for* the dual-route theory of inflection—that the regular past-tense rule is an informationally encapsulated module (see Fodor, 1983)—and subjected it to rigorous empirical scrutiny. Pinker et al. (e.g., Clahsen, 1999; Kim et al., 1991; Pinker, 1991, 1999, 2001) have claimed that the processing of regular inflection is driven by an innate mechanism that is unaffected by phonology, frequency, or semantics. Results from the two experiments reported here fail to support this claim. Rather, they have shown conclusively that semantics *do* affect regular past-tense comprehension, both of existing forms that may have been stored in memory, and of novel forms that need to be interpreted on-line.

As Pinker (1999) observed, it is more than reasonable to assume that the same basic process (or processes) are responsible for both past-tense production and comprehension. Ramscar (2002) showed that regular past-tense production—in elicited inflection tasks—was affected by semantics (see also Tabak et al., 2010; Woolams et al, 2009). The results reported here complement these findings and extend them, by providing an objective on-line measure of the effects of semantics on inflection (most previous studies of inflection have relied on subjective judgments and ratings to measure inflection processes, e.g., Kim et al., 1991; Prasada & Pinker, 1993; Ramscar, 2002; Ullman, 1999). The results of Experiments 1 and 2 showed—objectively—that participants found regular past-tense forms easier to process when the semantic contexts they were related to supported a regular form.

The pattern of results reported here thus accords well with a model of inflection that assumes that past-tense forms are computed (in both comprehension and production) by a process that discriminates between previously stored forms, taking into consideration factors such as phonological and semantic similarity and frequency. At the same time, these results are not so easily compatible with the idea that regular inflection is processed independently from the contents of memory nor with the claim that regular inflection is entirely unaffected by factors such as frequency and similarity (see Pinker, 1991, 1999, 2001). However, this does not mean that the dual-route model is necessarily wrong; these results no more disprove the idea that *some* regular inflection is carried out in this context-independent manner than does the existence of still more white swans "disprove" the idea of orange swans. Still, in light of these results, it is worth considering what it is that a context-independent rule is supposed to add to scientific accounts of inflection.

Given that these results show that homophone verb processing does not require a dual-route account, it follows that all inflections can—in principle—be processed in memory without recourse to an explicit, rule-based mechanism (see also Ramscar, 2002). More worryingly for a dual-route account, there is an increasingly large body of evidence showing that neither linguistic behavior nor the distribution of inflected forms across languages are easily reconciled with the claim that regular inflections are governed by context-independent rules (see e.g. Ambridge, 2010; Balling & Baayen, 2008; Baayen, McQueen, Dijkstra, Schreuder, 2003; Bien, Baayen, & Levelt, 2011; Hahn & Nakisa, 2000; Ramscar, 2002; Ramscar & Dye, 2011; Ramscar & Yarlett, 2007; Stemberger, 2002, 2004; Tabak et al., 2010; Woollams et al., 2009).

This evidence—and on a more mundane level, Occam's razor—militates against the often made claim that an explicit, context-independent rule is a necessary or even informative component of psychological explanations of inflectional processing (e.g. Clahsen, 1999; Gordon & Miozzo, 2008; Huang & Pinker, 2010; Pinker, 1991, 1999, 2001; Pinker & Ullman, 2002). At present, single-route accounts of inflection—in which the discrimination of forms is influenced by factors such as phonological and semantic similarity and frequency—provide more economical explanations of, and a better fits to, the available data. Accordingly, it seems likely that children do *not* learn the English past-tense rule in any explicit sense, and "rather than involving hypothesis testing about grammatical rules, learning involves accumulating information about statistical and probabilistic aspects of language" (Seidenberg & MacDonald, 1999). While linguists may distinguish between irregular and regular past-tense forms in English, it would seem that the psychological processes that govern language processing do not make this explicit distinction at all.

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APPENDIX 1

Items used in Experiment 1 (the semantic context sentences are highlighted)

fly—semantically similar to normal irregular usage

To promote business, the pesticide shop always stands a man in a giant fly costume at the entrance of their shop, to greet customers. This is especially fun for children. Whenever a child enters the shop, the greeter performs 'the fly'. *The child sits between the wings on the greeter's back, and they buzz up and down the aisles, ducking and swooping*. In the shop, the term to describe how the greeter greets children in this way is 'to fly them'. One hot day in June, sweating in his fly costume, I saw the greeter fly 40 children in a single afternoon. The look of tiredness on his face afterwards was really something.

fly—not semantically similar to normal irregular usage

To promote business, the pesticide shop always stands a man in a giant fly costume at the entrance of their shop, to greet customers. This is especially fun for children. Whenever a child enters the shop, the greeter performs 'the fly'. *The greeter tells the children jokes and gives out prizes.* In the shop, the term to describe how the greeter greets children in this way is 'to fly them'. One hot day in June, sweating in his fly costume, I saw the greeter fly 40 children in a single afternoon. The look of tiredness on his face afterwards was really something

food-drive—semantically similar to normal irregular usage

In June the students decided to hold weekend food-drives to help the homeless. *They cruised through the neighbourhood in a truck* and asked people to donate a can of food, or anything else they could spare. The students worked very hard. One Saturday I saw them food-drive for 8 long hours

food-drive—not semantically similar to normal irregular usage

In June the students decided to hold weekend food-drives to help the homeless. *They set up a booth in front of the local supermarket* and asked people to donate a can of food, or anything else they could spare. The students worked very hard. One Saturday I saw them food-drive for 8 long hours

drink—semantically similar to normal irregular usage

To promote business, the neighbourhood soda-fountain always stands a man dressed as a giant coke-bottle and holding a giant drinking straw at the entrance of their shop to greet customers. This is especially fun for children. Whenever a child passes by the shop, the greeter performs "the drink". *The greeter puts one end of the straw on the child's head, and then pretends to suck from the other end.* In the shop, the term to describe how the greeter greets children in this way is "to drink them". One hot day in June, I saw the greeter drink 200 children in a single afternoon.

drink—not semantically similar to normal irregular usage

To promote business, the neighbourhood soda-fountain always stands a man dressed as a giant coke-bottle and holding a giant drinking straw at the entrance of their shop to greet customers. This is especially fun for children. Whenever a child passes by the shop, the greeter performs "the drink". *The greeter dances around in his giant coke-bottle costume and twirls his giant straw.* In the shop, the term to describe how the greeter greets children in this way is "to drink them". One hot day in June, I saw the greeter drink 200 children in a single afternoon.

sink—semantically similar to normal irregular usage

Last summer Jim was really poor. He had to take a crummy job in a kitchen. All he got to do was sink dishes all day long. It was really dull. Jim didn't even get to wash the dishes. Other guys did that. *All he had to do was put them under the soapy water in the sink.* I thought he would hate it, but he didn't. Jim was a star. His boss says he'll always remember the sunny day in July when he saw Jim sink 400 plates in one hour.

sink—not semantically similar to normal irregular usage

Last summer Jim was really poor. He had to take a crummy job in a kitchen. All he got to do was sink dishes all day long. It was really dull. Jim didn't even get to wash the dishes. Other guys did that. *All he had to do was to take the dishes from the kitchen refuse station to the sink room and stack them on a bench ready for the dishwashers.* I thought he would hate it, but he didn't. Jim was a star. His boss says he'll always remember the sunny day in July when he saw Jim sink 400 plates in one hour.

APPENDIX 2

Items used in Experiment 2

frink—semantically similar to irregular (drink)

In a traditional spring rite at Moscow University Hospital, the terminally ill patients all frink in the onset of good weather, consuming vast quantities of vodka and pickled fish. Last year, his favourite vodka glass in hand, I saw cancer patient Ivan Borovich frink around 35 vodka shots and 50 pickled sprats. It is not recorded whether this helped in his treatment.

frink—semantically similar to regular (blink, wink)

In a classical symptom of Howson's syndrome, patients all frink in their right eye if they are left handed or left eye if right handed, their eyelids opening and closing rapidly and uncontrollably. Last year, while suffering extreme discomfort from his bad eye, I saw Howson's patient Ivan Borovich frink around 35 times per minute for days, causing severe damage to the muscles in his left eyelid.

Target—''Last year Ivan Borovich **frank/frinked** a lot.''

freep—semantically similar to irregular (sleep)

The Whanaka are a tribe that live in Antartica. In order to survive the extreme winters, the Whanaka all fatten themseleves up in autumn, and then eat a herb called wassule, which induces a very drowsy, somnabulent state that allows them to freep over the winter, enabling them to conserve energy. Because he ate too much wassule one year by accident, Whanaka head man Linus Banula somehow managed to freep through the following Spring as well. When he finally came to, he was very embarassed.

freep—semantically similar to regular (peep)

The Whanaka are a very timid tribe that live in Africa. When Whanaka venture out into narrow, shady streets, they always carry with them a wassule, which is a combination earhorn and periscope, that allows them to freep over and around obstacles, enabling them to avoid the shock of surprise encounters. One day, when he accidentally poked his wassule into a dark corner, I saw Whanaka head man Linus Banula freep into a nudist colony. The shock nearly killed the poor man.

Target—''Linus Banula **frept/freeped** accidentally.''

preed—semantically similar to irregular (breed)

A novel technique for systematically cross transferring a subset of plant DNA is used to preed new plant cell types. It was reported in ''Cells and Scientists''. Susan, a researcher who specialised in generating new plant cells, was impressed by the article, and after reading it, she followed the DNA cross transference method carefully and began to preed a new cell type in her garden which she hoped would be especially resistant to fungus infections.

preed—semantically similar to regular (weed)

A novel spray for selectively getting rid of unwanted predatory plants is used to preed new lawns and gardens in readiness for spring planting. It was described in "Plants and Gardeners." Susan, a gardener who specialised in preparing new lawns, was impressed by the article, and after reading it, she bought a can of the selective plant killing spray and used it. I saw Susan preed a new lawn bed in order to guarantee that only healthy grass would grow there.

Target—''After reading the article Susan **pred/preeded** in her garden.

clow—semantically similar to irregular (throw)

In the west of Detroit, where local people are particularly proud of their basketball skills, a very skillful, widely admired basketball technique is to clow one's ball, sending it soaring as high into the air as possible before landing it in the hoop. Last summer, I saw basketball fanatic Jim Skoggins clow his ball high into the air for an hour every day to practice this.

clow—semantically similar to regular (mow)

In the west of England, where local people are particularly fond of the quality of their green grass, a very fashionable gardening technique is to clow one's lawn, using a machine that stands grass upright, and clips the tops of the grass blades to a pre-selected shape. Last summer I saw gardening fanatic Jim Skoggins clow his lawn with just such a machine for an hour every day to keep it in tip top condition.
Target—Jim Skoggins **clew/clowed** for an hour a day.