The Role of Domain-General Inhibition in Inflectional Encoding: Producing the Past Tense

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Abstract

According to a prominent account of inflectional encoding (Pinker, 1999; Pinker & Ullman, 2002b), regular forms are encoded by a rule-governed combination of stems and affixes, whereas irregular forms are retrieved from memory while inhibiting rule application. Sahin, Pinker, and Halgren (2006) suggested that this concerns a domain-general mechanism. Previous research on domain-general inhibition has shown that when switching between tasks, languages, or phrase types, an asymmetrical switch cost is obtained, which has been attributed to overcoming previous inhibition of the predominant response. If generating an irregular form involves rule inhibition, then switching from an irregular to a regular form should require overcoming previous inhibition and delay responding. We tested this in three experiments on producing the past tense in Dutch. We observed that an asymmetrical switch cost is obtained when switching between inflecting and reading verbs, but not when switching between encoding irregular and regular forms. These results suggest that the production of irregular forms does not involve the type of domain-general inhibition involved in switching between tasks, languages, or phrase types.

Keywords: inflectional encoding; inhibition; past tense; task switching; switch cost asymmetry.

1. Introduction

Since the 1980s, researchers have debated the issue of whether regular and irregular inflected forms of words, like past tense forms of verbs (e.g., *walked*, *held*), are both generated by associative memory (e.g., Rumelhart & McClelland, 1986; McClelland & Patterson, 2002a) or the regulars by rules and the irregulars by associative memory (e.g., Pinker, 1999; Pinker & Ullman, 2002b). In a recent review, Kemmerer (2015) concludes that the evidence favors the latter view based on "the simple fact that compelling double dissociations between precisely matched regulars and irregulars have been documented in at least some studies" (p. 385; see McClelland & Patterson, 2002a, 2002b, and Pinker & Ullman, 2002a, 2002b for a debate). For example, in a seminal study, Ullman et al. (1997) observed that patients with Parkinson's disease, possibly having a rule application problem, were better at irregulars than regulars, whereas patients with Alzheimer's disease, with a memory retrieval problem, showed the reverse.

Applying the suffixation rule would be the predominant response in generating the past tense of verbs in languages like English and Dutch[1]. Pinker (1999) and Pinker and Ullman (2002b) assume that in generating an irregular past tense, rule application must be prevented by inhibition. Pinker and Ullman stated, "If an inflected form for a verb (V) exists in memory, as with irregulars (e.g. *held*), it will be retrieved; a signal indicating a match blocks the operation of the grammatical suffixation process via an inhibitory link from lexicon to grammar, preventing the generation of *holded*" (p. 457). According to Sahin, Pinker, and Halgren (2006), "Activation of cognitive control and inhibition regions may be required by irregular inflection for two reasons: blocking of the regular rule to prevent overregularizations (e.g., *holded*), and suppression of conflicting responses among competing irregular patterns (e.g., *brang* or *brung*) that are generalized from families of similar irregular forms" (p. 556)[2].

We tested the suggestion of Sahin et al. (2006) that domain-general inhibition is the mechanism by which rule application is blocked. To this end, we had participants switch between producing regular and irregular past tense forms. Previous research on domain-general inhibition has shown that when participants switch between tasks, languages, or phrase types, an asymmetrical switch cost may be obtained (e.g., Meuter & Allport, 1999; Sikora, Roelofs, Hermans, & Knoors, 2016; Sikora & Roelofs, 2018; Verhoef, Roelofs, & Chwilla, 2009). For example, in switching between picture naming in the first or second language, it takes longer to switch to the stronger first language than to the weaker second language (Meuter & Allport, 1999). Such asymmetrical switch costs have been explained by assuming that in naming in the weaker second language, the stronger first language needs to be inhibited. Consequently, in switching from the second to the first language, the inhibition of the first language needs to be overcome, delaying naming in the first language. We utilized the same logic in examining inhibition in inflectional encoding. If generating an irregular form involves the domain-general type of inhibition of rule application, then switching from an irregular on one trial to a regular on the next trial should require overcoming of the

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[1] In Dutch, the past tense is formed by adding the suffix *–te* to stems ending in a voiceless obstruent, and *–de* elsewhere (Booij, 1995).

[2] Dutch irregular past tense is quasi-regular like English, with different *families* of irregular forms.

previous inhibition, which should delay responding[3]. There should be no such delay in switching from a regular to an irregular, because inhibition of rule application is not involved in producing regulars. We tested this in three experiments.

2. Experiment 1

2.1. Method

2.1.1. Participants. Twenty healthy Dutch adults participated in the experiment for monetary compensation or course credits. All had corrected-to-normal vision and gave written consent.

2.1.2. Materials. Stimuli were Dutch verbs, 50 with a regular (e.g., *werken – werkte*) and 50 with an irregular (e.g., *nemen – nam*) past tense. They were matched on $\log_{10}$ transformed word and lemma frequency (SUBTLEX-NL, Keuleers, Brysbaert & New, 2010), with mean word and lemma frequencies of 2.75 and 3.90 for the regulars and 2.87 and 3.86 for the irregulars.

2.1.3. Procedure and Design. Between-participants, all verbs appeared in both switch and repeated conditions. A trial preceded by a verb of the same regularity was a repeat trial, and a trial preceded by a verb of the other regularity was a switch trial. All verbs were presented once per block over three blocks in a pseudorandom order with verb regularity changing every other trial (Figure 1A). This predictable alternate-runs paradigm allows for a comparison of repeat and switch trials in the same block without compromising the switch-cost effect. It is a standard method used in the produce the past-tense form as quickly and accurately as possible. The microphone recorded the onset of their response for the full duration of the trial. Incorrect responses, self-corrections, or disfluencies were coded as errors.switching literature (Monsell, 2003). Each trial began with the visual presentation of the infinitive of a verb followed by a blank screen (Figure 1B). Participants had to produce the past-tense form as quickly and accurately as possible. The microphone recorded the onset of their response for the full duration of the trial. Incorrect responses, self-corrections, or disfluencies were coded as errors.

2.1.4. Analysis. RTs for correct responses were analyzed using linear mixed-effects models (LMEMs) and errors with generalized linear mixed-effects models (GLMEMs) with the lmerTest package (version 3.01-1) (Kuznetsova, Brockhoff & Christensen, 2017) in R (R Core Team, 2018). We began with full models with fixed effects for regularity (regular/irregular) and trial type (repeat/switch), their interaction, and random slopes for subjects and items. When these models failed to converge, we simplified their structure by first removing the random slopes for items and then for subjects.

[3] Note that the direction of inhibition is not arbitrary in language switching (i.e., only L1 is inhibited or L1 is inhibited more strongly than L2) nor in regularity switching (inhibition is applied to the regular rule in producing an irregular).

To quantify the strength of the evidence, we performed Bayesian statistical analysis using JASP (Love, Selker, Verhagen, Marsman, Gronau, Jamil et al., 2017)[4].

Due to technical issues, the last 16 trials of one of the participants were not recorded but the results for the remainder trials were still included in the analysis. The first trial of every block, incorrect responses, and RTs < 200 ms were removed from the RT analysis.

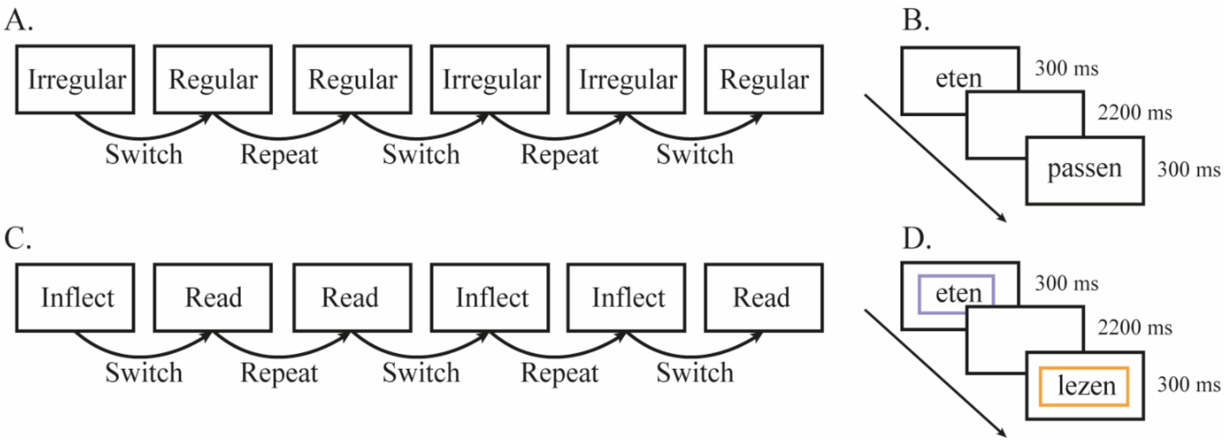

Figure 1. Sequence of trials (A) and events (B) for Experiment 1 and the inflection-only part of Experiment 2, and the sequence of trials (C) and events (D) for task-switching part of Experiment 2.

2.2. Results

Figure 2 shows the RT and error results, and Table 1 the outcomes of the statistical analyses. The final model for the errors included fixed effects of regularity and trial type, and random intercepts for subjects and stimuli. There was only a main effect of regularity. The final model for the RTs included fixed effects of regularity and trial type, and by-subject random slopes for regularity and trial type, and by-item random slopes for trial type. There was no main effect of regularity, trial type, or interaction. The Bayesian analyses confirmed these results, indicating moderate evidence for no interaction.

2.3. Discussion

Accuracy was lower for irregulars than regulars, but there was no difference in RT, no switch cost, and no interaction. Thus, we find no evidence that the production of irregulars involves inhibition of the regular rule. However, it remains possible that our switching paradigm was, for unclear reasons, not powerful or sensitive enough to yield an asymmetrical switch cost. We examined this possibility in our second experiment.

[4] A Bayes factor (BF_{10}) of 1-3 indicates “anecdotal”, 3–10 “moderate”, 10–30 “strong”, 30–100 “very strong”, and > 100 “extreme” evidence for H_1, and of 0.33-1 “anecdotal”, 0.10-0.33 “moderate”, 0.03-0.10 “strong”, 0.01-0.03 “very strong”, and < 0.01 “extreme” evidence for H_0 (Wagenmakers et al., 2017).

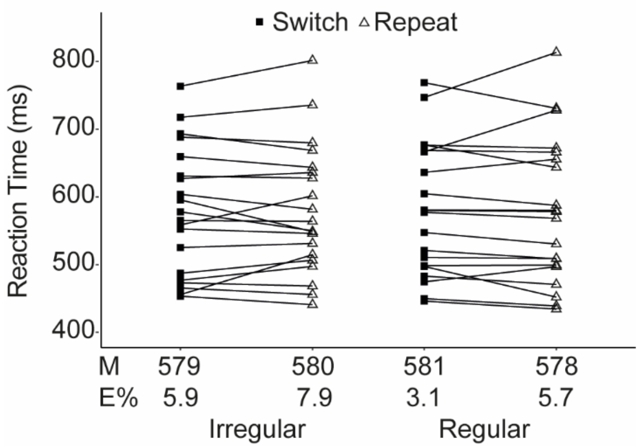

Figure 2. Mean naming response time (RT) by regularity (regular, irregular) and trial type (repeat, switch) for each participant and group-level mean RT (M) and mean error percentage (E%) in Experiment 1.

Table 1. Results for the GLMEMs for the error rates, LMEMs for the RTs, and Bayes factors for Experiment 1

		β	***SE***	***z- or t-value***	***p***	***BF*₁₀**
Error	Regularity	-1.45	.36	-4.03	< .001	14.96
	Trial type	.30	.36	1.95	.051	7.3
	Regularity × Trial type	.42	.27	1.54	.124	.31
RTs	Regularity	2.28	8.80	.26	.796	.23
	Trial type	.79	6.04	.13	.897	.23
	Regularity × Trial type	-3.58	9.58	-.37	.712	.31

3. Experiment 2

The second experiment had two separate parts, each with two blocks. In the inflect-only part, participants switched between inflectional encoding of regulars and irregulars, as in Experiment 1. In the task-switching part, they switched between reading aloud and inflecting. Reading is the predominant response to a written word, and therefore inflection is expected to require inhibition of the reading response. Consequently, switching from inflection to reading should require overcoming the previous inhibition of reading, which should delay responding. Observing an asymmetrical switch cost would demonstrate that our paradigm is powerful and sensitive enough to detect such a cost.

3.1. Method

3.1.1. Participants, Materials, Design, and Procedure. Twenty new Dutch adults were recruited from the same pool as for Experiment 1. Ninety-six Dutch verbs were used as stimuli, 48 with a regular and 48 with an irregular past tense, a subset of the stimuli used in Experiment 1.

The design and procedure of the inflection-only part were the same as in Experiment 1. For the task-switching part, a repeat trial was preceded by a trial where participants had to perform the same task, and a switch trial was preceded by a trial where they had to perform the other task. Within each block, regulars and irregulars were presented in small mini-blocks of 24 trials of the same regularity type, with task changing every second trial (Figure 1C). With this manipulation we can distinguish between inhibition related to task switching and inhibition specific for irregular production. Participants were presented with the infinitive of a verb surrounded by a colored frame followed by a blank screen (Figure 1D). For one of two possible colors, they had to produce the past tense (inflect task) and for two other colors they had to read the word aloud (read task). Two colors were used for each task type such that colors always alternated between trials to avoid a confound of task switch and color switch.

3.1.2. Analysis. Statistical analysis for the inflection-only part was similar to Experiment 1. For the task-switching part, we started with a GLMEM for errors and LMEM for RTs with regularity (regular/irregular), trial type (repeat/switch), and task (read/inflect) as fixed effects and with random slopes for subjects and items. If these models failed to converge, we simplified them as in Experiment 1. We also performed Bayesian analyses.

3.2. Results

3.2.1. Inflection-only part. Figure 3 shows the RT and error results, and Table 2 gives the outcomes of the statistical analyses. The final model for the errors included fixed effects of regularity and trial type, and random intercepts for subjects and items. There were main effects of trial type and regularity.

The final model for the RTs included fixed effects of regularity and trial type, by-subject random slopes for regularity and trial type, and by-item random slopes for trial type. We found no effect of regularity, trial type, or interaction. The Bayesian analyses confirmed these results, indicating moderate evidence for no interaction.

3.2.2. Task-switching part. Figure 4 shows the RT and error results, and Table 3 gives the outcomes of the statistical analyses. The final model for the errors included fixed effects of regularity, trial type, and task, and random intercepts for subjects. There were main effects of trial type and task, but no interaction.

The final model for the RTs included fixed effects of regularity, trial type and task, by-subject random slopes for regularity, and by-item random intercepts. Participants were slower on inflect than read trials, but there was no effect of regularity or trial type. Participants were slower on switch than repeat trials, but only for the read task. Regularity did not interact with trial type or task. The interaction between trial type and task was not modulated by regularity. The Bayesian analysis confirmed these results, indicating extreme evidence for an asymmetrical task-switch cost.

Table 2. Results for the GLMEMs for the error rates, LMEMs for the RTs, and Bayes factors for the inflection-only part of Experiment 2

		β	***SE***	***z- or t-value***	***p***	***BF*₁₀**
Error	Regularity	-.65	.29	-2.26	.024	12.38
	Trial type	-.66	.20	-3.22	.001	54.23
	Regularity × Trial type	-.29	.34	-.84	.402	.34
RTs	Regularity	8.49	13.409	.63	.530	.31
	Trial type	-6.10	6.92	-.88	.378	.51
	Regularity × Trial type	-6.37	10.80	-.59	.558	.31

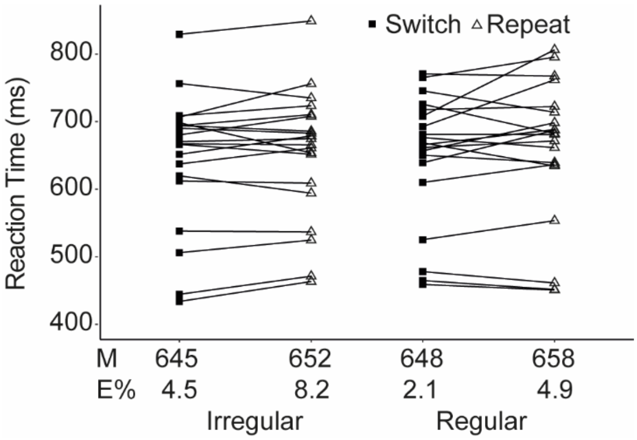

Figure 3. Inflection-only part of Experiment 2: Mean naming response time (RT) for each participant and group-level RT mean (M) and mean error percentage (E%) for the inflect task by regularity (regular, irregular) and trial type (repeat, switch).

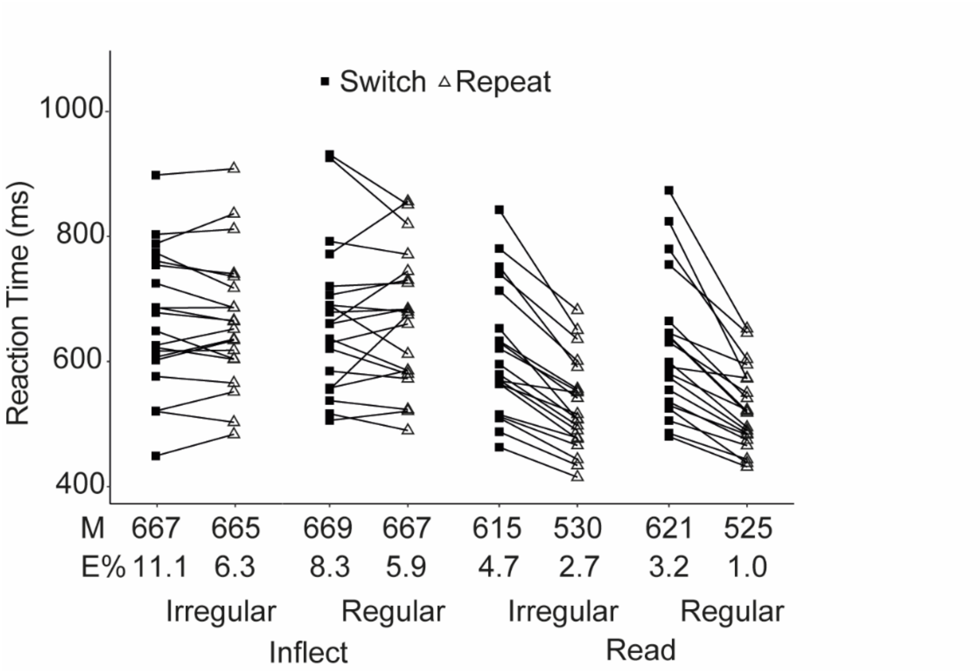

Figure 4. Task-switching part of Experiment 2: Mean naming response time (RT) for each participant and group-level mean RT (M) and mean error percentage (E%) for the inflect and read tasks grouped by regularity (regular, irregular) and trial type.

3.3. Discussion. In the inflection-only part, we replicated the results of Experiment 1 showing no cost for switching between regulars and irregulars. In the task-switching part, participants were slower on task switch than task repeat trials, but only for the read task, again with no regularity effects. Thus, an asymmetrical switch cost was obtained for switching between tasks, but not for switching between irregulars and regulars.

These results demonstrate that our paradigm is powerful enough to reveal an asymmetrical switch cost, although not for inflection. However, regulars and irregulars appeared in fixed order, which for unclear reasons, may have affected the results. Experiment 3 addressed this issue by randomizing regularity across trials.

Table 3. Results for the GLMEMs for the error rates, LMEMs for the RTs, and Bayes factors for the task-switching part of Experiment 2

		β	***SE***	***z- or t-value***	***p***	***BF₁₀***
Error	Regularity	-.07	.27	-.27	.784	.61
	Trial type	.62	.24	2.62	.009	11.18
	Task	-.92	.34	-2.74	.006	2.93E05
	Regularity × Trial type	-.25	.35	-.73	.468	.26
	Regularity × Task	-.90	.59	-1.53	.125	.23
	Trial type × Task	-.02	.43	-.05	.958	.32
	Regularity × Trial type × Task	.83	.72	1.15	.249	.11
RTs	Regularity	1.45	12.99	.12	.911	.17
	Trial type	.33	9.12	.04	.972	328.26
	Task	-133.96	8.78	-15.26	< .001	1.54E17
	Regularity × Trial type	4.20	12.85	.33	.744	.24
	Regularity × Task	-7.86	12.36	-.64	.525	.23
	Trial type × Task	81.28	12.74	6338	< .001	6.92E06
	Regularity × Trial type × Task	9.15	17.94	.51	.610	1.35

4. Experiment 3

4.1. Participants. Twenty new Dutch adults were recruited from the same pool as for the other experiments.

4.2. Materials, Design, Procedure, and Analysis. Same as in the inflection-only part of Experiment 2, except that trials were now randomized with the constraints that there were equal numbers of repeat and switch trials and no more than five trials of the same regularity in a row.

4.3. Results. Figure 5 shows the RT and error results, and Table 4 gives the outcomes of the statistical analyses. The final model for the errors included fixed effects of regularity and trial type, and random intercepts for subjects and items. There was only a main effect of trial type.

The final model for the RTs included fixed effects of regularity and trial type, by-subject random slopes for regularity and trial type, and by-item random slopes for trial type. We found a main effect of regularity and an interaction: Participants were slowest on regular repeat trials, with the Bayesian analysis providing strong evidence for the interaction.

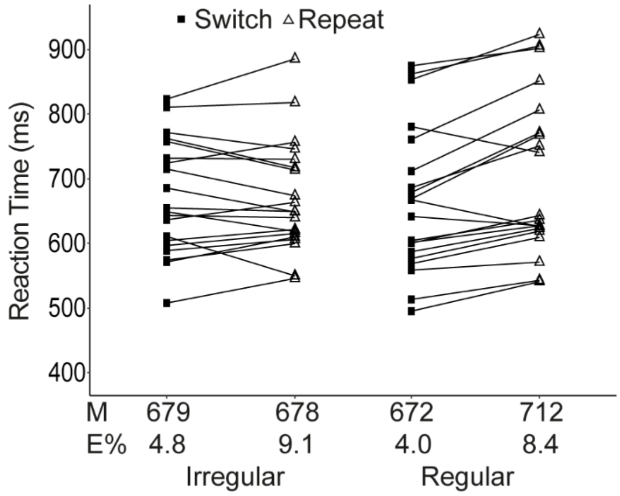

Figure 5. Mean naming response time (RT) by regularity and trial type for each participant and group-level mean RT (M) and mean error percentage (E%) in Experiment 3.

Table 4. Results for the GLMEMs for the error rates, LMEMs for the RTs, and Bayes factors for Experiment 3

		β	***SE***	***z- or t-value***	***p***	BF_{10}
Error	Regularity	-0.09	.16	-.57	.570	.24
	Trial type	-.69	.19	-3.68	< .001	24.3
	Regularity × Trial type	-.12	.28	-.42	.677	.33
RTs	Regularity	34.2	16.20	2.11	.04	.77
	Trial type	-.58	9.24	-.06	.95	2.77
	Regularity × Trial type	-38.9	13.95	-2.79	.01	5.22

4.4. Discussion. With a randomized order of trials, we found a repetition rather than a switch cost for regulars. Perhaps participants prepared for memory retrieval (i.e., irregular production) yielding a repetition cost for regulars. Importantly, our results show no evidence for rule inhibition.

5. General Discussion

In three experiments, we tested the suggestion of Sahin et al. (2006) that domain-general inhibition is the mechanism by which rule application is blocked in producing the past tense of irregular verbs. If producing an irregular form involves inhibition of rule application, then switching from an irregular to a regular verb should also require overcoming of the previous inhibition, delaying responding. Contrary to this prediction, we observed no cost for switching between irregulars and regulars. A switch cost for irregulars and regulars was absent even though switching between inflecting and reading did yield an asymmetrical switch cost, replicating the findings in the literature on switching between tasks, languages, and phrase types. Thus, our findings challenge the assumption that domain-general inhibition is the mechanism by which rule application is blocked in producing the past tense of irregular verbs.

Our results, however, do not exclude all forms of inhibition from being involved in irregular production, but only the domain-general type of inhibition that is involved in switching between tasks, languages, and phrase types. It remains possible that rule inhibition is achieved by another type of inhibition that is not showing switch costs, which may be further examined in future research.

To conclude, our results provide evidence that the production of irregular forms does not involve the domain-general type of inhibition that is involved in switching between tasks, languages, or phrase types.

Data statement

The data reported in this article are available in the Open Science Framework Repository https://osf.io/szp8b/

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Appendix. List of stimuli used in experiments 1 and 2

Irregulars		Regulars	
Infinitive	Past tense	Infinitive	Past tense
staan	stond	werken	werkte
nemen	nam	halen	haalde
helpen	hielp	bellen	belde
brengen	bracht	voelen	voelde
liggen	lag	volgen	volgde
spreken	sprak	kennen	kende
lijken	leek	stoppen	stopte
zoeken	zocht	pakken	pakte
lopen	liep	spelen	speelde
schieten	schoot	zorgen	zorgde
vallen	viel	hoeven	hoefde
zuigen	zoog	leren	leerde
sterven*	stierf*	noemen	noemde
eten	at	heten*	heette*
slapen	sliep	stellen	stelde
drinken	dronk	redden	redde
rijden	reed	hopen	hoopte
slaan	sloeg	sturen	stuurde
schrijven	schreef	trouwen	trouwde
zenden	zond	wonen	woonde
lezen	las	snappen	snapte
kopen	kocht	kloppen	klopte
winnen	won	missen	miste
trekken	trok	raken	raakte
dragen	droeg	leggen	legde
liegen	loog	gooien	gooide
klinken	klonk	passen	paste
breken	brak	slagen*	slaagde*
vliegen	vloog	groeien	groeide

hangen	hing	tonen	toonde
kiezen	koos	lachen	lachte
zinken	zonk	leiden	leidde
roepen	riep	dansen	danste
steken	stak	starten	startte
springen	sprong	rennen	rende
bieden	bood	kussen	kuste
grijpen	greep	storen	stoorde
snijden	sneed	vluchten	vluchtte
blijken	bleek	stappen	stapte
dwingen	dwong	dromen	droomde
schrikken	schrok	bouwen	bouwde
vangen	ving	roken	rookte
zwijgen	zweeg	tellen	telde
stinken	stonk	openen	opende
drijven	dreef	delen	deelde
treffen	trof	smeken	smeekte
blazen	blies	branden	brandde
gelden*	gold*	schamen	schaamde
duiken	dook	vrezen	vreesde
schenken	schonk	eisen	eiste

Note. Items marked with a * were removed in Experiment 2.

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