

memorization is demonstrated by similar shifts in other populations with putative dysfunctional frontal/grammatical system, as demonstrated by frequency effects and other methods (Ullman, 2001). Finally, the data presented here have implications for therapeutic approaches for the recovery of language.

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## Sex differences in the neurocognition of language

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We have argued, based on several lines of evidence, that language processing depends upon two neurocognitive systems (Ullman, 2001). The mental lexicon, which contains (at least) idiosyncratic word-specific information (e.g., for irregular past-tenses; *break-broke*), depends on the temporal-lobe-based declarative memory system. Aspects of the mental grammar underlying the real-time rule-based composition of complex linguistic representations (e.g., regular past-tenses; *play + -ed*) depend on a frontal/basal-ganglia procedural system that also subserves motor skills.

Females are better than males at remembering words (Kimura, 1999). We posited a sex difference in the processing of complex linguistic representations: females may tend to memorize previously encountered complex representations (e.g., regular past-tenses; *played*) that males generally compose on-line (*play + -ed*). Both sexes should memorize idiosyncratic lexical knowledge (*break-broke*); and both should rule-compute new complex forms (*proy + -ed*), because these could not be memorized. We have obtained converging evidence for these predictions from five studies:

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(1) *Frequency effects: English.* If past-tense representations are retrieved from memory, more frequent ones should be remembered faster. If they are rule-products, such past-tense frequency effects are not expected. Sixteen men and 17 women produced regular/irregular past-tenses (dependent measure: reaction-time). Men showed past-tense frequency effects for irregulars ( $p < .005$ ) but not regulars (n.s.). Women showed past-tense frequency effects for both verb types ( $p < .005$ ).

(2) *Frequency effects: Spanish.* Sixteen men and 17 women produced Spanish regular (*pescar-pesco*) and irregular (*pensar-pienso*) first-person-singular present-tense forms (dependent measure: reaction-time). Men showed past-tense frequency effects for irregulars ( $p < .001$ ) but not regulars. Women showed the effects for both (irregulars:  $p < .05$ ; regulars:  $p < .001$ ).

(3) *Parkinson's disease* is associated with basal-ganglia degeneration, leading to suppressed movements (hypokinesia) (Boller & Grafman, 1995). Fifteen men and 14 women with Parkinson's disease produced past-tenses. For the men, past-tense production rates of regulars but not irregulars correlated (over subjects) with hypokinesia, whereas production rates of irregulars but not regulars correlated with lexical abilities (object naming);  $ps < .05$  or n.s. The women's production rates of both past-tense types correlated with lexical abilities ( $ps < .01$ ) but not hypokinesia. Moreover, the most hypokinetic males ( $n = 4$ ) were impaired only at regulars, compared to age- and sex-matched control subjects (interaction:  $p < 0.05$ ); the most hypokinetic women ( $n = 6$ ) were impaired at neither.

(4) *Event-related potentials (ERPs)* reflect the real-time electrophysiological brain activity of cognitive processes that are time-locked to the presentation of target stimuli. Difficulties in lexical/semantic processing elicit centro-parietal negativities ("N400s") that peak about 400 milliseconds post-stimulus and depend upon bilateral temporal-lobe structures. Difficulties in grammatical processing yield early (150–500 ms) left anterior negativities ("LANs"), linked to rule-based automatic computations and left frontal structures, and posited to reflect grammatical/procedural processing; and late (600 ms) centro-parietal positivities ("P600s") associated with controlled processing and posterior brain regions, and posited not to reflect grammatical/procedural processing (Boller & Grafman, 1995; Friederici, Hahne, & von Cramon, 1998).

Twenty-six men and 26 women were visually presented with anomalous and matched correct control sentences probing four conditions: regular and irregular past-tenses (e.g., Yesterday I *took*/\**take* a pill), syntactic word-order (*Peter bought Betty's house at*/\**at house the beach*), and lexical/semantic processing (*John drove the tractor*/\**pocket into the field*). In both sexes, incorrect (stem) forms of irregular verbs elicited N400s. Crucially, regular past-tense violations yielded a LAN in males but an N400-like posterior negativity in females. In both sexes, semantic incongruities elicited an N400; this had a larger amplitude among the women, underscoring lexical/semantic neurocognitive sex differences. The syntactic word-order violations yielded a LAN in men. Women instead displayed a posterior negativity, larger in the left hemisphere. A statistical analysis comprising both syntactic and regular past-tense violations revealed a shared effect, across the two conditions, of a significantly more left and anterior distribution among men than women, which moreover did not differ between the two types of violations. Finally, all three grammatical violations (syntactic word-order and *both* past-tense types), but not the lexical/semantic incongruities, elicited the expected late posterior P600 components. As predicted, these did not differ in distribution or amplitude between the sexes.

(5) *Hormone replacement therapy.* The word-learning sex differences are linked to temporal-lobe structures and estrogen (Maki, Zonderman, & Resnick, 2001). We gave 10 post-menopausal women and 12 age-matched men hormone replacement therapy (women: estrogen; men: testosterone, the main source of estrogen in men) and placebo

in a double-blind crossover study testing past-tense production. Hormone therapy (compared to placebo) in both sexes increased production of real and novel irregular forms (*break-broke, spling-splung*) ( $p < 0.05$ ), with no placebo/treatment by male/female interaction. Performance at novel regulars (*blick-blicked*) decreased with hormone therapy ( $p < 0.05$ ; no interaction with sex), likely due to increased irregularizations (*blick-bluck*). Importantly, accuracy at real regulars (*swayed*) increased in women ( $p < 0.05$ ) but decreased in men ( $p < 0.01$ ). The study underscores the memorization of real regular past-tenses by women but not men and suggests that sex hormones (estrogen/testosterone) improve lexical retrieval/processing but not rule-based computations.

These experiments support the language sex difference hypothesis, in expressive and receptive language, in morphology and at least in some aspects of syntax; experiment five implicates estrogen in these effects. No performance differences were found in the studies of healthy untreated adults, suggesting that the neurocognitive sex differences do not lead to obvious achievement differences. The data have educational and clinical implications, and strongly suggest that language studies should include sex as a design factor.

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# The effect of sex hormones on language processing

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Previous studies suggest a dissociation in the neurocognitive bases of language. The mental lexicon of stored words is an associative memory that depends on the

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