

Arabic Morphology in the Neural Language System

Sami Boudelaa, Friedemann Pulvermüller, Olaf Hauk, Yury Shtyrov,
and William Marslen-Wilson

Abstract

■ There are two views about morphology, the aspect of language concerned with the internal structure of words. One view holds that morphology is a domain of knowledge with a specific type of neurocognitive representation supported by specific brain mechanisms lateralized to left fronto-temporal cortex. The alternate view characterizes morphological effects as being a by-product of the correlation between form and meaning and where no brain area is predicted to subserve morphological processing per se. Here we provided evidence from Arabic that morphemes do have specific memory traces, which differ as a function of their functional properties. In an MMN study, we showed that the abstract consonantal root, which conveys se-

mantic meaning (similarly to monomorphemic content words in English), elicits an MMN starting from 160 msec after the deviation point, whereas the abstract vocalic word pattern, which plays a range of grammatical roles, elicits an MMN response starting from 250 msec after the deviation point. Topographically, the root MMN has a symmetric fronto-central distribution, whereas the word pattern MMN lateralizes significantly to the left, indicating stronger involvement of left peri-sylvian areas. In languages with rich morphologies, morphemic processing seems to be supported by distinct neural networks, thereby providing evidence for a specific neuronal basis for morphology as part of the cerebral language machinery. ■

INTRODUCTION

Derivational morphology, the domain of knowledge concerned with the structure and formation of words, has been a controversial linguistic component in terms of its cognitive role and its neural implications for the brain systems underpinning language functions (Marslen-Wilson & Tyler, 2007; Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005; Vannest, Polk, & Lewis, 2005; Devlin, Jamison, Matthews, & Gonnerman, 2004; McKinnon, Allen, & Osterhout, 2003; Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000; Rueckl, Mikolinski, Raveh, Miner, & Mars, 1997; Schreuder & Baayen, 1995; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Seidenberg, 1987). The key question in this debate has been whether morphology is a basic aspect of language or whether it is an epiphenomenon of the systematic relationships underlying the form and meaning of words (Seidenberg & Gonnerman, 2000; Marslen-Wilson & Tyler, 1997; Marslen-Wilson et al., 1994; Seidenberg, 1987).

Our understanding of the cognitive role of derivational morphology has been significantly informed by behavioral studies looking at a wide range of languages that varied in terms of the word building principles they rely on and in terms of the overall richness of their morphological systems (Boudelaa & Marslen-Wilson, 2005; Frost, Forster, & Deutsch, 1997; Schreuder & Baayen, 1995; Marslen-Wilson et al., 1994; Caramazza, Laudanna, & Romani, 1988; Taft,

1979). Critical in this respect has been the recent research into Semitic languages like Arabic and Hebrew, which shows a clear dissociation between form-based, meaning-based, and morphology-based effects and has consequently contributed to shifting the focus of the debate from whether morphological factors play a cognitive role to how and when such factors affect the dynamics of processing and the internal architecture of the lexicon (Boudelaa & Marslen-Wilson, 2004, 2005; Frost, Deutsch, & Forster, 2000; Frost, Deutsch, Gilboa, Tannenbaum, & Marslen-Wilson, 2000; Frost et al., 1997; Caramazza et al., 1988; Taft, 1979).

In contrast to the substantial cross-linguistic behavioral research into derivational morphology, the data about the neural underpinning of this aspect of language are scarce, somewhat inconsistent, and derived mainly from studies conducted on English or related Indo-European languages (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Vannest et al., 2005; Davis, Meunier, & Marslen-Wilson, 2004; Devlin et al., 2004; Marangolo, Piras, Galati, & Burani, 2004; McKinnon et al., 2003). Thus, although Davis et al. (2004) and Devlin et al. (2004) found no evidence for brain areas that are specifically responsive to morphological processing, Bozic et al. (2007), using a long lag repetition priming task, did report a significant reduction in BOLD response in the left inferior frontal gyrus for morphologically structured words. In addition, using fMRI and a memory encoding task in which subjects had to remember visually presented simple words and morphologically complex words, Vannest et al. (2005) found that decomposable

derived words (e.g., *aptness*) showed increased neural activation in the left inferior frontal gyrus and in the basal ganglia relative to nondecomposable suffixed words (e.g., *minority*) and monomorphemic words (e.g., *address*). Marangolo et al. (2004) examined the production of derivationally complex forms in Italian, using an overtly compositional task, and report a somewhat mixed pattern of results, with derivational word-formation processes engaging both frontal and parietal regions. McKinnon et al. (2003) also found that nonwords made up of existing bound morphemes (e.g., **intain* made up of *in~* and *~tain* as in *retain*) elicit an N400 similar to that elicited by real words, suggesting that these morphologically complex nonwords were analyzed in a similar way as complex real words.

In view of this evidence, the status of derivational morphology as a neurally distinct domain of knowledge is still uncertain. It is also arguably the case that research limited to English and other Indo-European languages with similar concatenative morphologies is insufficient to provide the basis for broader generalizations about morphology and its neural underpinnings. What is needed is the cross-linguistic scope sufficient to build a language theory that captures the general characteristics of the human language faculty and acknowledges at the same time the specificities of each language (Bornkessel & Schlesewsky, 2006). The present study is a step in this direction, using ERPs and taking advantage of the richness of Semitic morphology to probe the neural correlates of Arabic *roots* and *word patterns*, two morphemic units that differ in terms of their structural, distributional, and functional properties.

Features of Arabic Morphology

Semitic morphology provides a sharp contrast with the more widely studied Indo-European morphologies. In this respect, the contrast between Arabic and English is particularly telling. These two languages differ in at least three fundamental ways related to the role of morphology. First, although many English words have no morphological structure (e.g., *car*, *caravan*, *table*), there is no such thing as a morphologically simple word in Arabic. Every surface form is morphologically complex, featuring at least two abstract bound morphemes, a *root* and a *word pattern*, which differ in their form, function, and distributional characteristics. In terms of form, roots are exclusively made up of consonants (e.g., {*ktb* *writing*, {*str* *concealing*}), whereas word patterns are primarily composed of vowels (e.g., {*faʕal*}; {*faaʕal*}), although they can feature some consonants as well (e.g., {*mafʕal*}, {*ʔafʕal*}). The letters “ʕʕl” are placeholders indicating where the first, the second, and the third letters of the root are to be inserted, respectively. Functionally, roots are like content stems in English in that they carry a semantic meaning that will be shared to various degrees by their derivatives. The meaning of *writing* inherent in the root {*ktb*}, for example, surfaces in many derived forms containing this root (e.g.,

{*kitaab*} *writing*; [*kitaabah*] *book*; [*maktuub*] *written*). By contrast, word patterns are composite morphemes, both conveying grammatical information about the surface form on the one hand and supplying its phonological structure.¹ The pattern {*mafʕal*} for example signals that the first, second, and third consonants of the root should surface in the position of the /f/, /ʕ/, and /l/, respectively. At the same time, this pattern conveys a *place noun* meaning, indicating a characteristic location where the action described by the root consonants takes place. Thus, the form [*maktab*] refers to a *place where one writes* (i.e., *office*) and [*maʕrab*] to a *place where one drinks* (i.e., *refreshment stand*; Versteegh, 1997; Holes, 1995; Wright, 1995).

A second major point of difference between Arabic and English morphology relates to the way surface word forms are constructed and how these relate to the relevant constituent morphemes. Morphemes in English are appended linearly (concatenated) one after the other (e.g., *dark* + *-ness* = *darkness*), whereas in Arabic, a root like {*ktb*} *writing* is interleaved with a word pattern (e.g., {*faʕal*}, meaning *active, perfective*) such that they surface in a discontinuous nonlinear manner in a word like [*katab*] *write*. This nonconcatenative interleaving of root and word pattern morphemes in the Arabic surface form means that these morphemes are experientially abstract in a way that does not hold for morphemes in concatenative systems such as English, which generally occur as separable individual phonetic forms. The Arabic morphemes never occur directly as phonetic entities in the language and must instead be inferred from underlying distributional patterns. These are major cross-linguistic differences both in basic mechanisms of complex word formation and in the abstractness of the morphemic entities being combined to create such complex forms.

The third point of difference pertains to the way the two languages rely on morphology to encode different aspects of meaning. Consider, for example, the concept of *causativity*—the process of causing someone to do something or causing something to happen. There are three major linguistic procedures that can be used to express this concept. The first is purely lexical, using specific lexical items that denote causal concepts (e.g., *drop*, *cause to fall*; *feed*, *cause to eat*). The second is a syntactic procedure using phrases that denote causal volition (e.g., *have one's hair cut*, *make someone happy*). The third is a morphological procedure that combines stems and specific causative morphemes to build morphological causatives (e.g., *widen*, *shorten*). Of the three procedures, English relies least often on the morphological option. In contrast, Arabic relies solely on morphological procedures, where a root is combined with a causative word pattern (e.g., {*faʕʕal*} *active, perfective, causative*) to generate forms like [*kattab*] *cause to write*, [*ʕallam*] *cause to learn*.

The consequence of the nonlinear nature of Arabic morphology, the pervasiveness of its morphological complexity

and its heavy reliance on morphological procedures to encode various aspects of meaning, is that morphological composition and decomposition seem to be obligatory processes in Arabic language production and language comprehension. This is consistent with a large body of behavioral research that shows a strong dissociation in Arabic (and in Hebrew) between morphological effects and semantic and form-based effects (e.g., Boudelaa & Marslen-Wilson, 2005; Frost et al., 1997). The systematic operations of morphological assembly invoked upon speaking Arabic and the parsing operations required to understand it lead us to expect to see extensive neural networks dedicated to morphological processing and representation in this language.

The available behavioral data for these languages show a clear dissociation between morphemic effects on the one hand and form-based and meaning-based effects on the other. This dissociation is observable not only in covert masked priming as in Indo-European languages but also in overt cross-modal and auditory–auditory priming (Boudelaa & Marslen-Wilson, 2001; Frost, Deutsch, Gilboa, et al., 2000). More specifically, prime and target pairs that are morphologically related but semantically unrelated (e.g., [katiibatun]–[maktabun] *squadron–office*) prime each other equally well in covert and overt priming. Similarly, prime and target pairs sharing only a word pattern and which therefore are not semantically related (e.g., [xudsuuʃun]–[ħuduuθun] *submission–happening*) also show reliable facilitation in covert and overt priming tasks. This suggests that morphological decomposition is a critical property of both prelexical and central representations of lexical forms in Arabic. In addition to this, the differences in functions, distributional characteristics, and phonological makeup between roots and word patterns have significant consequences for the way these units operate cognitively (Boudelaa & Marslen-Wilson, 2005). These behavioral results are further corroborated by preliminary neuropsychological data showing selective impairment of performance on roots (Prunet, Béland, & Idrissi, 2000) and word patterns (Barkai, 1980), which is consistent with the possibility of different neural correlates for Semitic morphemes.

The Present Study

In this research, we used EEG to ask (a) whether Arabic morphology is processed by discrete neuronal networks and (b) whether the networks related to different types of morphemes (roots and word patterns) are distributed over distinct sets of brain regions.

The specific brain response we will use is the MMN, which has been used as an indicator of learned memory circuits supporting linguistic representations. To obtain an MMN, participants are typically presented with two auditory stimuli while focusing their attention on an irrelevant visual distractor, such as a silent movie (Näätänen, 1995, 2001; Näätänen & Alho, 1997). The MMN response

is elicited by infrequent *deviant* stimuli randomly presented among frequent *standard* stimuli. To derive the MMN, we subtracted the average waveform elicited by the standard stimulus from that of the deviant stimulus.

MMN, like the N400, is part of a family of responses that exhibit sensitivity to expectancy violations at different levels of processing (Pulvermüller & Shtyrov, 2006; Näätänen, 1995; Kutas & Hillyard, 1984). The MMN and the N400, however, seem to have quite different properties, most notably in situations where the mismatch is not consciously detected. The N400 response is relatively attenuated (or even absent) when subjects' attention is directed toward other stimuli as in dichotic listening (Bentin, Kutas, & Hillyard, 1995; McCarthy & Nobre, 1993). By contrast, the MMN response is evoked even in the absence of attention as when a subject reads a book or watches a silent movie (Pulvermüller, Shtyrov, Kujala, & Näätänen, 2004). Because the manner in which the MMN reflects specific cognitive processes, in terms of the size and distribution of the effect, is generally unaffected by attentional factors, this suggests that the MMN acts as a measure of automatic processes (Pulvermüller, Shtyrov, Hasting, & Carlyon, 2008).

Importantly, recent research indicates that the MMN is sensitive to higher order cognitive processes and is able to capture the brain activities triggered by different aspects of linguistic input. It therefore provides potential access to the neural activity subserving the processing of linguistic components such as phonology, semantics, and morphology. Pulvermüller and Shtyrov (2003), for example, showed that the MMN is sensitive to the morphosyntactic properties of the input in English. Standard and deviant phrases like *we come–we comes* generate a left-anterior MMN response that is larger than that triggered by matched standard-deviant phrases where the first two segments form a nonword as in *fn come–fn comes*. In further studies, inflectional affixes in English and Finnish elicited a left-lateralized MMN with generators focused in left fronto-temporal peri-sylvian regions (Shtyrov & Pulvermüller, 2002). Together with earlier neuropsychological work, this suggests that morphemes acting as markers of grammatical information have a neural correlate in left-lateralized neuronal circuits, possibly confined to the language areas or a specific region thereof.

Here we investigated the MMN response to words presented as deviant stimuli among other words used as standards. The standard and the deviant stimuli differed either by a root consonant (e.g., [ʃariis]–[ʃariif] *bride–corporal*) or by a word pattern vowel (e.g., [ʃariis]–[ʃarus] *bride–bridegroom*). To control for physical or acoustic differences between the word–word comparisons, we also investigated MMN responses to meaningless pseudo-words that differed either by the final root consonant (e.g., *[niriis]–*[niriif]) or by the final word pattern vowel (e.g., *[niriis]–*[niruus]). Because the MMN response is known to be experience dependent (Pulvermüller et al., 2004), we hypothesized that the response to words would

not only be greater than that elicited by nonwords, but that the MMN enhancements for the two deviant words [ʕariif] and [ʕariis] would differ from each other in their cortical topographies.

Specifically, because the root morpheme is the bearer of semantic meaning and plays a role akin to that played by monomorphemic content words in Indo-European languages, we expected it to be cortically processed by a widely distributed neuronal network capturing information about its form and its meaning. In contrast, the word pattern, which is a grammatical morpheme whose role is similar to that played by grammatical morphemes and function words in Indo-European languages, was expected to trigger a left-lateralized neuronal processing component. These predictions follow from the earlier findings in these languages of different cortical distributions for content words and for function words and affixes (e.g., Pulvermüller, Lutzenberger, & Birbaumer, 1995; Mohr, Pulvermüller, & Zaidel, 1994; Caplan, 1992).

METHODS

Subjects

Twenty native Arabic speakers (mean age = 24 years) took part in the experiment. All were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971) and had no left-handed family members. All participants had normal hearing and no history of neurological problems. Each subject gave his or her written informed consent to participate in the experiments.

Stimuli

A large pool of exemplars of each of the words [ʕariis] *bridegroom*, [ʕariif] *corporal*, and [ʕaruus] *bride* and the nonwords *[niriis], *[niriif], and *[niruus] were recorded by a native speaker of Arabic and digitized with a sampling rate of 44 kHz, then downsampled to 22 kHz using the CoolEdit program. Four experimental pairs, two word–word pairs and two nonword–nonword, were selected so that the overall F0 frequencies of the syllables preceding the critical vowels differed by 3% or less in each pair. Moreover, there was no statistically significant difference between the F0 contour, the duration, or the F1, F2, and F3 values of the sequence /iis/ in the word [ʕariis] and the nonword *[niriis]. Similarly, no statistical differences were found on any of these measures between the sequence /iif/ in the word [ʕariif] and the nonword *[niriif]. Finally, the distribution of the spectral peaks, the duration, and amplitude was similar in the offset fricatives /s/ and /f/ across the words and nonword.

The words [ʕariis] *bride* and [ʕariif] *corporal*, which feature the same word pattern {faʕiil}, but different roots, {ʕrs} and {ʕrf}, were used as standard and deviant in the root condition. The first four segments of the word func-

tioning as the deviant [ʕariif] (i.e., [ʕarii]) were cross-spliced to the word [ʕariis] (see Figure 1). The resulting two words were 500 msec long and were acoustically identical up to the deviation point. This occurred at 360 msec from word onset and was placed at the beginning of the final fricative consonant.² This word–word pair was closely matched in terms of overall duration and deviation point to a pair of standard-deviant nonwords (*[niriis]–*[niriif]) consisting of the nonexisting word pattern *{fiʕiil} and the nonexisting roots *{nrs} and *{nrf}, respectively. The same cross-splicing procedure was applied to these nonword pairs as to the word–word pairs, with the [niri] portion of *[niriif] being cross-spliced to *[niriis].

In the word pattern condition, the standard was again [ʕariis] *bride* but the deviant was [ʕaruus] *bridegroom*. The two words contained the same root {ʕrs} but differed with respect to their word patterns. This was {faʕiil} in the standard but {faʕuul} in the deviant. Following a similar procedure as for the root stimuli, the first three segments of the word [ʕaruus] (i.e., [ʕar]) were cross-spliced to the standard [ʕariis]. The resulting words were each 500 msec in duration, with a deviation point occurring at 140 msec.³ This word–word pair was also closely matched to a nonword–nonword pair (*[niriis]–*[niruus]) consisting of a nonexisting word pattern *{fiʕiil} and a nonexisting root *{nrs}. The same cross-splicing procedure was applied as for the word–word pairs, with the [nir] portion of *[niruus] being cross-spliced to *[niriis].

Procedure

Stimuli were pseudorandomized and presented in four blocks through headphones at comfortable loudness with an SOA of 1000 msec. Each block consisted of 150 deviants presented against the background of 850 standards. Participants were explicitly instructed to ignore the acoustic stimuli and were allowed to watch a silent movie of their choice in an electrically shielded and dimly lit sound-proof booth.

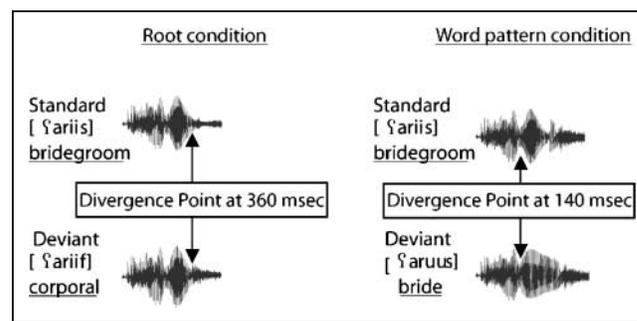


Figure 1. Acoustic waveforms of the word stimuli used in the root and the word pattern conditions showing the divergence (or splice) point for each standard/deviant pair. Members of each pair are acoustically identical up to the divergence point (see text).

EEG Recording

During the auditory stimulation, the electric activity of the subject's brain was continuously recorded (band-pass = 0.01–100 Hz; sampling rate 500 Hz) with a 64-channel EEG set up (Neuroscan Labs) using Ag/AgCl electrodes mounted in an extended 10-20 system (1) electrode cap (Easy Cap, Neuromedical Supplies, Sterling, VA). The electrode Cz was used as the reference during the recording. To control for eye movement artifacts, we monitored the horizontal and the vertical EOG from electrodes located on the outer canthi as well as below and above the right eye. The ground was placed at electrode position FPz (on the forehead), and impedances were kept below 5 k Ω .

Data Analysis

Neurophysiological data were filtered off-line (band-pass = 1–30 Hz), and ERPs for standards and deviants were computed separately by averaging the corresponding epochs within each block, starting 100 msec before the deviation point and ending 1000 msec after word onset. Epochs with excessive voltage variation (e.g., eye artifacts > 100 μ V) at any EEG or EOG channel were discarded from averaging. ERPs were average referenced, and the 100-msec interval preceding the deviation point in each condition was used for baseline correction. The data of three participants were removed due to high noise levels (Sound Noise Ratio < 2). ERPs were computed for each of the remaining 17 subjects and for each electrode. All ERP averages were aligned to 100 msec baseline relative to the onset of the deviation point.

RESULTS

Using a series of running *t* tests, we sought to determine, looking across all electrodes, whether the deviant items elicited different ERP responses compared with their respective standards in the word–word and the nonword–nonword conditions. A response was considered relevant when (a) it occurred at least 100 msec after the deviation point, (b) it was sustainable over two time windows of 20 msec or more, and (c) it involved fronto-central and/or adjacent electrodes (i.e., lines AF7, F7, and FT7) typically engaged by the MMN response as established in the literature. We then calculated the MMN response by subtracting the averaged standard response from the averaged deviant response for words and for nonwords (Näätänen, 1995) and submitted them to a four-way ANOVA with morpheme (root, pattern), lexicity (word, nonword), laterality (left, middle, right), and anterior/posterior (four lines of electrodes: AF7 F7, FT7, and T7) as within-subject factors. Recordings from 36 electrodes located over the frontal and the central areas of the two hemispheres (four rows of electrodes running posterior–anterior by nine

rows running left to right) were used for these analyses. The time windows we reported are 160–180 msec after the splice point for the root and 250–270 msec after the splice point for the word pattern. Larger time windows spanning 50, 80, and 100 msec around the peak were also analyzed and showed similar results to the time window we report. The use of a short time window maintains comparability with previous research where similar windows were used (Pulvermüller & Shtyrov, 2003; Pulvermüller, 2001). All the *p* values that we report for the ANOVAs are Greenhouse–Geisser corrected.

For the root condition, the results show that there was a significant Bonferroni-corrected difference between the ERP of the standard and deviant stimulus starting from 160 msec after the deviation point for both the word–word comparison, $t(16) = 4.36, p < .05$ (i.e., ([{ariis}]–[{ariif}] *bridegroom–corporal*), and the nonword–nonword comparison, $t(16) = 5.00, p < .05$ (i.e., *[niriis]–*[niriif]). Parallel effects were found in the word pattern condition with a Bonferroni-corrected reliable difference between standard and deviants emerging at 250 msec after the deviation point for the word–word comparison, $t(16) = 6.20, p < .05$ (i.e., ([{ariis}]–[{aruus}] *bridegroom–bride*), and the nonword–nonword comparison, $t(16) = 5.83, p < .05$ (i.e., *[niriis]–*[nirus]).

Combining the data from the noun and the word-pattern conditions revealed a significant main effect of morpheme, $F(1,16) = 42.36, p < .001$, suggesting that the MMN response was different for the root and the word pattern morphemes. The main effect of lexicity, $F(1,16) = 13.60, p < .001$, was also significant, reflecting the stronger MMN response in the word–word cases than the nonword–nonword cases. The two-way interaction between morpheme and lexicity was significant, $F(1,16) = 10.73, p < .01$. Furthermore, the factor morpheme interacted significantly with anterior/posterior, $F(3,16) = 9.15, p < .01$, and lexicity, $F(3,16) = 3.88, p < .05$. Most importantly, the three-way interactions between the factors Morpheme, Lexicity, and Laterality, $F(2,16) = 6.67, p < .05$, and between Lexicity, Morpheme, and Anterior/Posterior, $F(3,16) = 15.13, p < .01$, were both significant, suggesting that the laterality and the topography of the MMN were modulated by morpheme type and the lexical status of the items being heard.

These interactions were unpacked in a further series of planned comparisons using Bonferroni protection levels. For the root comparison, there was a significant difference between the MMN for the word–word response and the nonword–nonword response, $F(1,16) = 11.64, p < .05$. The effects of laterality were significant for the nonword–nonword comparison, $F(2,16) = 6.77, p < .05$, but not for the word–word comparison, $F(2,16) < 1$. There was no difference between the three levels of laterality (i.e., left–middle–right) in the word–word comparison. For the nonword–nonword comparison, middle was significantly different from left, $t(16) = 3.45, p < .05$, but not from right, and the left–right contrast was not significant. This

is consistent with the claim that the MMN response for the root in the word context is subserved by a bihemispheric fronto-central network, whereas the MMN response for the nonword is mainly focused at central recording sites and primarily driven by the acoustic differences between the standard and the deviant nonwords. The anterior/posterior contrast was significant for the word–word comparison, $F(3,16) = 6.74, p < .05$, as well the nonword–nonword comparison, $F(3,16) = 12.80, p = .05$. Turning to the word pattern effects, there was a significant difference between the MMN response generated in the word–word context and the nonword–nonword context, $F(1,16) = 5.41, p < .05$. The effects of laterality were significant for the word–word comparison, $F(2,16) = 5.80, p < .05$, but not for the nonword–nonword comparison, $F(2,16) = 2.26, p = .13$. In particular, although there was a significant difference between left and middle, $t(16) = 3.37, p < .05$, and between left and right, $t(16) = 2.7, p < .05$, in the word–word comparison, the middle-left comparison was not reliable. This was because the MMN response for the pattern

in the word context lateralizes clearly to the left. For the nonword–nonword contrast, neither the left–right contrast nor the middle-right contrast were significant, whereas the middle-left contrast was reliable, $t(16) = 2.60, p < .05$, indicating that the pattern in the nonword context is more symmetric and most prominent at fronto-central electrodes. Finally, the effects of anterior/posterior were not significant either for the word–word, $F(3,16) < 1$, or the nonword–nonword comparison, $F(3,16) < 1$. These different effects are depicted in Figures 2 and 3, which represent the difference waves for the word–word and the nonword–nonword contrasts in the root and the word pattern conditions, respectively.

Minimum Norm Estimates of Cortical Generators

To obtain an estimate of the distributed brain activity underlying root and pattern processing, we calculated minimum norm current estimates on the surface of the average

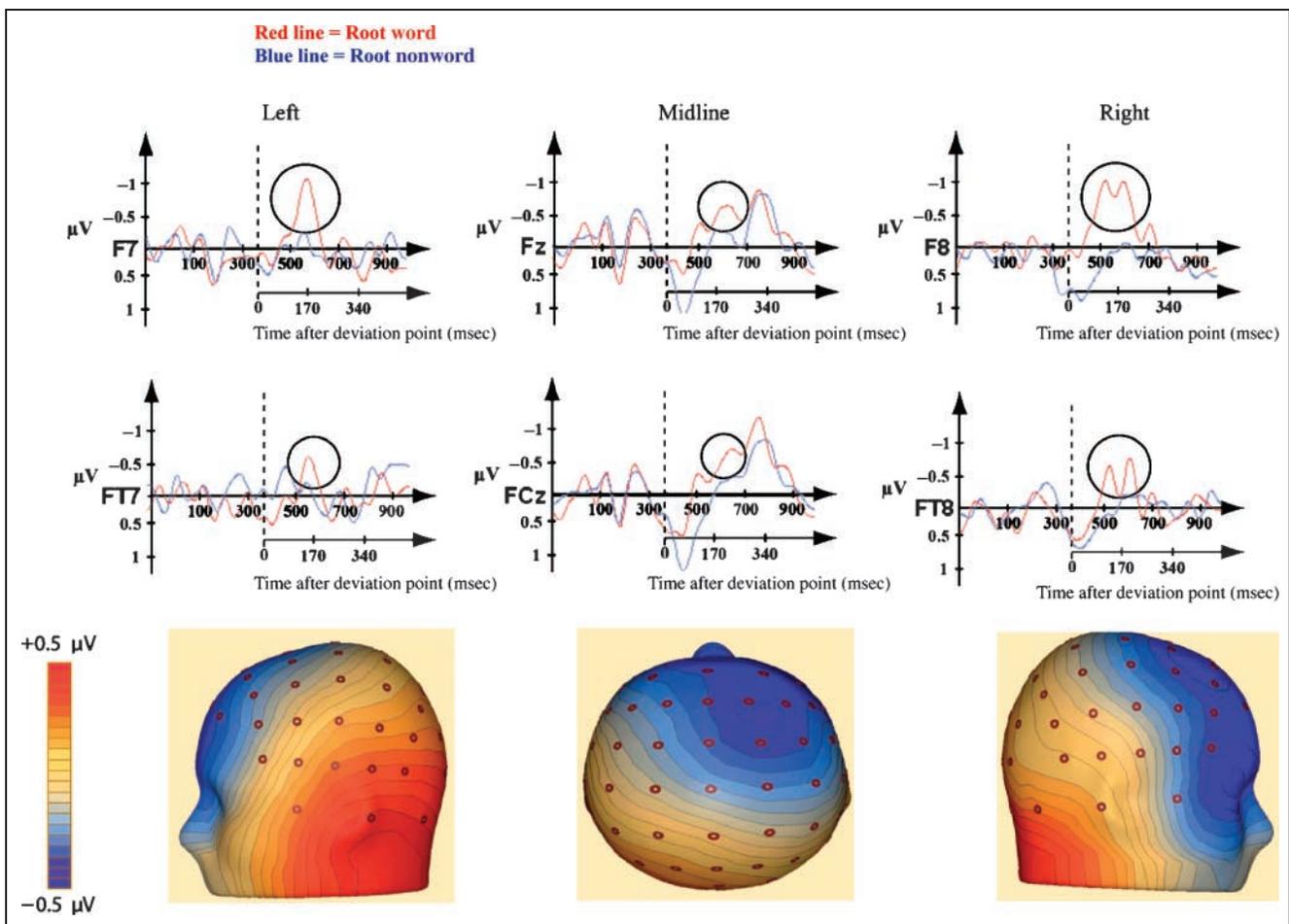


Figure 2. Root conditions: MMN curves at left (F7, FT7), midline (Fz, FCz), and right (F8, FT8) electrode sites, as elicited by the deviant word [ʒariif] *corporal* in the context of the standard [ʒariis] *bridegroom* (red curve) and by the nonword deviant *[niriif] in the context of the nonword standard *[niriis] (blue). The secondary *x*-axis indicates timing from the acoustic divergence point. The small circle on each wave indicates the MMN peak at that electrode. Left, right, and top views of the topographic map of the MMN response for the word pairs [ʒariis]–[ʒariif], for the time-window 250–270 msec from deviation point, are also shown, illustrating the bihemispheric fronto-central profile of the root response.

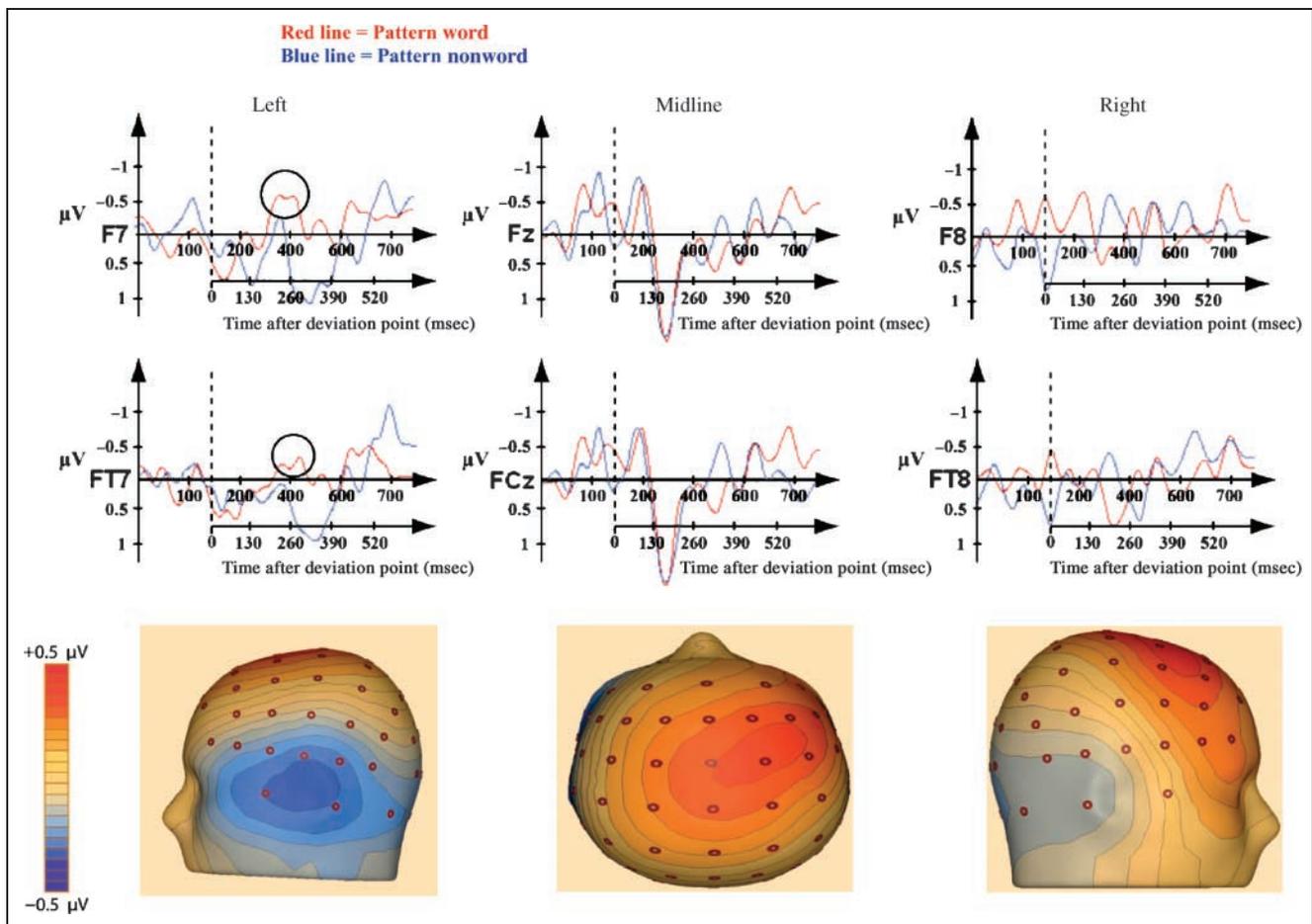


Figure 3. Word pattern conditions: MMN curves at left (F7, FT7), midline (Fz, FCz), and right (F8, FT8) electrode sites, as elicited by the deviant word [ʃaruus] *bride* in the context of the standard [ʃariis] *bridegroom* (red curve) and by the nonword deviant *[niruus] in the context of the nonword standard *[niriis] (blue). The secondary x-axis indicates timing from the acoustic divergence point. The small circle on each wave indicates the MMN peak (where present) at that electrode. Left, right, and top views of the topographic map of the MMN response for the word pairs [ʃariis]–[ʃaruus], for the time window 160–180 msec from deviation point, are also shown, illustrating the left-lateralized profile of the word-pattern response.

Montreal brain using a standard isotropic realistic head model. This was done using the Besa software package (Megis Software, Munich, Germany). The Minimum Norm method was chosen as it relies on minimal modeling assumptions (Hauk, 2004). Figure 4 presents the cortical sources of the MMN response at 260 msec after the deviation point for the word pattern and at 170 msec for the root. The source constellation estimates are more strongly left lateralized for the word pattern, which shows a well-focused left fronto-temporal distribution. This is corroborative evidence that root and word pattern processing engage differential neural networks and have different implications for lateralization. Together with the significant interactions of the morpheme type factor (root vs. pattern) and the scalp topography factors (anterior/posterior and laterality), the hypothesis about differential laterality of content word stems and derivational grammatical morphemes was supported by these source localization analyses. The source estimates further suggest that the laterality contrast is mainly due to differences in

left-hemispheric activations, with roots and word patterns differing both in strength and in topography.

DISCUSSION

It is clear from Figure 2 that root processing was supported by fronto-central neural networks that are distributed over the two hemispheres, a pattern of activation that is similar to the symmetric, nonlateralized ERP responses to content words presented in isolation (Pulvermüller, 2001; Pulvermüller et al., 1995; Mohr et al., 1994; Neville, Mills, & Lawson, 1992), and also to the N400 responses seen in semantically incongruous contexts. The latter effects usually emerge at 300–500 msec (Kutas & Hillyard, 1980, 1984)—although, when stimulus variance is controlled for and minimized, early precursors can be seen that are similar in latency to the MMN (Penolazzi, Hauk, & Pulvermüller, 2007). By contrast, the MMN response in the word pattern condition is strongly left lateralized

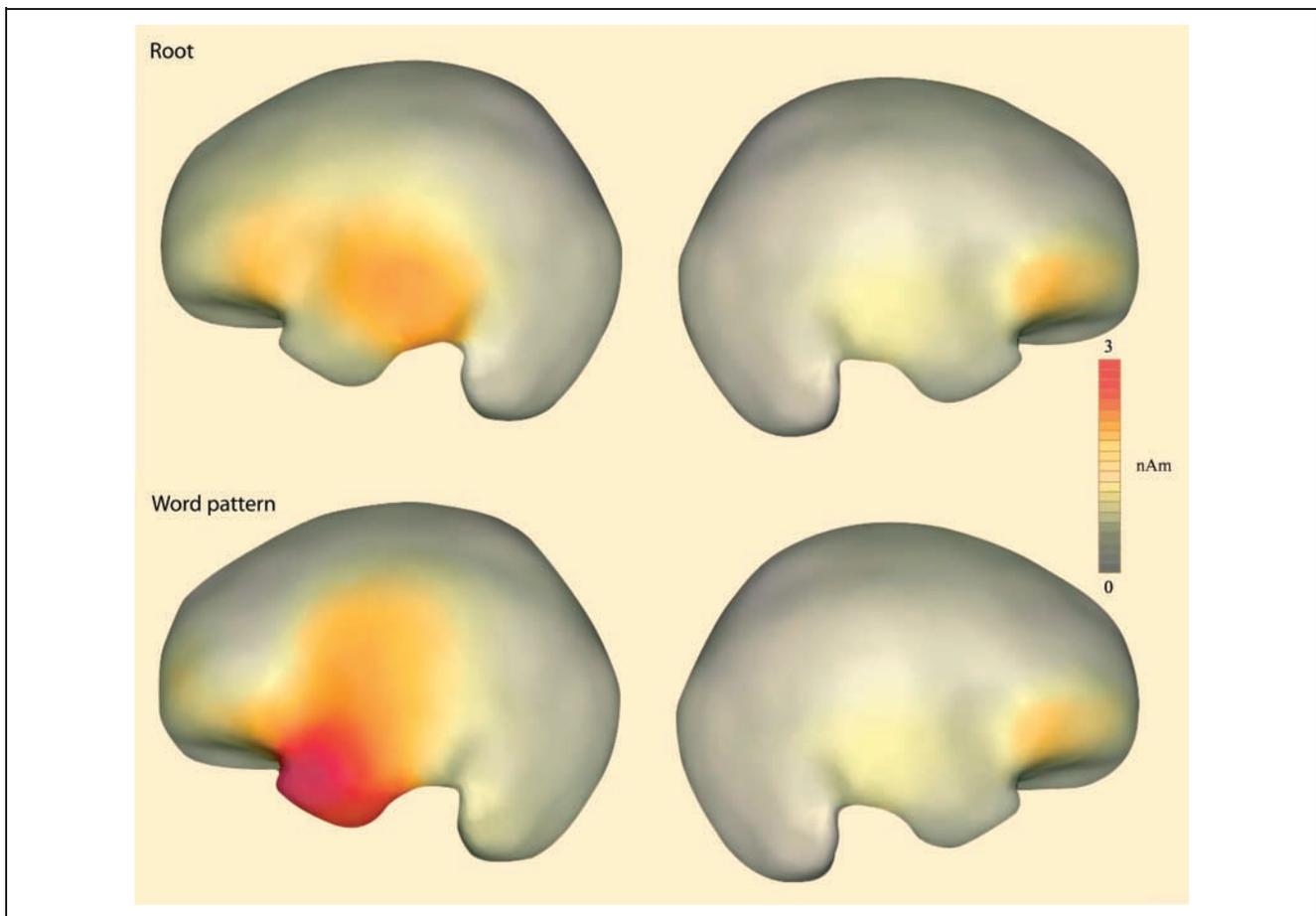


Figure 4. Grand average localization of MMN generators. (upper panel) The minimum-norm estimate of the left and right hemispheric sources of the root effect at 170 msec after the deviation point. (lower panel) The minimum-norm estimate of the left and right hemispheric sources of the word pattern effect at 260 msec after the deviation point. Note the difference in laterality, which is substantiated by statistical analyses.

and most pronounced in the recordings above the left peri-sylvian areas as shown in Figure 3. Left-lateralized processing has been reported for function words and grammatical morphemes based on normal subjects' data and clinical data (e.g., Lück, Hanhne, & Clahsen, 2006; Tyler, Marslen-Wilson, & Stamatakis, 2005; Shtyrov & Pulvermüller, 2002; Weyerts, Penke, Dohrn, Clahsen, & Müte, 1997; Caplan, 1992; Neville, Nicol, Barss, Forster, & Garrett, 1991; Geschwind, 1970). The present data extend the finding of strongly left-lateralized brain responses to the Arabic word pattern, which is a derivational morpheme.

The similarity between the topography of the word pattern MMN and its time course (250–350 msec) to those of the lateralized negativities in previous research (Lück et al., 2006; Weyerts et al., 1997) suggests that the parsing of a regularly inflected form into a stem and a suffix in Indo-European languages and the parsing of an Arabic word into a root and word pattern may be cognitively and neurophysiologically similar processes, although involving linearly combined morphemes in one case and nonlinearly combined morphemes in another. This is consistent with the cross-linguistic similarities in the grammatical functions subserved by these different morphemes,

although the Arabic word pattern has the extra role of conveying information about the phonological structure of the surface form.

At this point, the question arises of the validity of a strictly morphological interpretation of the present results, given the differences in the semantic relationships underlying the standard and the deviant in the root and word pattern conditions. The words in the root condition (i.e., [ʕariis]–[ʕariif] *bridegroom–corporal*) are semantically unrelated, whereas those in the word pattern condition are semantically related ([ʕariis]–[ʕaruus] *bridegroom–bride*). Although these pairs reflect the different functional properties of roots and word patterns as typically experienced by native speakers, this raises the possibility that the different MMN profiles in the two conditions reflect semantic rather than morphological differences.

To evaluate the plausibility of a purely semantic account of the data, we ran an ANCOVA using semantic relatedness between standard and deviant in each condition as a covariate. The semantic relatedness measure was obtained as part of a large semantic judgment test carried out by many participants, including those who took part in the MMN experiment. Participants were asked to rate related

and unrelated word pairs on a 9-point scale of semantic relatedness, with 9 representing *very related in meaning* and 1 representing *very unrelated in meaning*. The average semantic relatedness ratings for the [ʕariis]–[ʕariif] and the [ʕariis]–[ʕaruus] pair were 1.73 and 7, respectively. To ensure that semantic relatedness as a covariate is independent from morpheme as a grouping factor and that it provides an adequate basis of variability (and thus enhance the ability of a repeated measure ANCOVA to adjust the effects of various contrasts), we used the difference between the ratings for the word pattern and the root conditions provided by each subject. These difference scores, which averaged 5.27, with an *SD* of 1.28, and with a range of values from 3 to 7, provided sufficient variability and were entered as a covariate in a three-way ANCOVA with morpheme, laterality, and anterior/posterior as independent variables.⁴ This gave us a way of estimating whether the semantic properties of the relationships between standard and deviant in each condition, varying on a participant by participant basis, did affect the ERP results and whether the effects of morphological factors would survive any such correction.

In fact, after adjustment by the covariate, the main effects of morpheme, $F(1,16) = 6.67, p < .01$, and anterior posterior, $F(3,16) = 25.50, p < .001$, were still significant, as was the interaction between them, $F(3,16) = 4.59, p < .03$. The main effect of laterality was not significant, but the critical interaction between laterality and morpheme was still present, $F(2,16) = 9.37, p < .02$. This indicates that the difference between the MMN responses generated by the root and the word pattern does not only reflect semantic differences per se but differences between morphemic units, which play different roles in the language. Further Bonferroni-corrected planned comparison using semantic relatedness as a covariate revealed that for the root condition, the effect of laterality was not significant ($F < 1$), whereas that of anterior posterior was significant, $F(2,16) = 6.74, p < .05$. For the word pattern condition, the effects of laterality were significant, $F(2,16) = 5.90, p < .05$, but those of anterior posterior were not ($F < 1$).

GENERAL DISCUSSION

The present investigation addressed two questions. First, whether in a morphologically rich language like Arabic, abstract morphemic units like roots and word patterns have specific brain signatures, and second whether these signatures dissociate both temporally and topographically depending on the functional properties of the morphemic unit itself. We first review our evidence for the presence of specific brain signatures for Arabic roots and patterns. We next examine the differential profiles of these signatures. Finally, we relate our findings to results from research looking at semantic and morphosyntactic violations using the N400 and the LAN responses.

Do Roots and Patterns Have Specific Neural Signatures?

The data show that a standard-deviant pair differing by their final root consonant [ʕariis]–[ʕariif] *bridegroom–corporal* elicits a significant bilateral fronto-temporal MMN response compared with nonword pairs also differing by a final pseudoroot consonant. This MMN enhancement can be taken as a sign of an increased activation of neural networks subserving the processing of the consonantal root in Arabic. Alternatively, however, it could be argued that the standard-deviant pair [ʕariis]–[ʕariif] *bridegroom–corporal* is simply two different lexical items comparable with a pair of English words diverging at their final phoneme such as *state* and *stake*, so that the effects do not specifically implicate a root-based (or morpheme-based) level of representation as opposed to a word level. However, on a word-based view, words differing by a word pattern (e.g., [ʕariis]–[ʕaruus] *bride–bridegroom*) should also be considered as two different lexical items and should accordingly show an MMN response similar in space and time to that evoked by words differing by a root morpheme (Ratcliffe, 2004; Gafos, 2003; Benmamoun, 1998). Our results do not support this. Instead [ʕariis]–[ʕaruus], differing by a word pattern vowel, elicits a left-lateralized MMN response distinct from the bilateral fronto-central negativity produced by [ʕariis]–[ʕariif], which differs by a root consonant.

The differences in the topography of the MMN profiles generated here by roots and word patterns clearly support a morpheme-based approach to Arabic (Boudelaa & Marslen-Wilson, 2005; Prunet et al., 2000) and are consistent with the different functional roles played by these morphemes in the language. Roots are generally content morphemes, which convey referential meaning (Holes, 1995; McCarthy, 1981, 1982). During the course of language acquisition, roots are associated with different modalities and functions. For example, acquiring the root {smk} *fish* involves, among other processes, the integration of information about its various sensory properties as well as higher order functional information. This multidimensional information requires the coordination of neural activities in various sensory and higher order cortices in both hemispheres, and this seems to result in widely distributed bi-hemispheric neural circuits subserving root processing and representation. Even roots that are more abstract, such as {ktb} *write*, plausibly link to a wide range of sensorimotor activities as well as to higher order properties. In contrast, word patterns are function morphemes that neither co-occur with certain sensory motor events nor invoke specific functional activities outside the linguistic domain. Consequently, the neural circuits representing a word pattern will tend to be focused around specialized language areas in the left hemisphere (Pulvermüller et al., 1995; Mohr et al., 1994), potentially subserving specific combinatorial functions (e.g., Marslen-Wilson & Tyler, 2007). In this context, it is important to note that the differential laterality seen for different types of morpheme does not require

the application of the MMN method. For example, ERP laterality differences between function and content words have been found in lexical decision tasks (Pulvermüller et al., 1995; Neville et al., 1992), whereas regular and irregular verbs can elicit left-lateralized (e.g., LAN) versus symmetric (N400) effects (Lück et al., 2006; Friederici, 2002; Weyerts et al., 1997).

From a more linguistic perspective, note that this overall set of results is difficult to accommodate within a stem-based view of Arabic (Ratcliffe, 2004; Heath, 2002). On such a view, the standard word [ʕariis] stands in the same relationship to both the deviants [ʕariif] and [ʕaruus], so that there is no basis for expecting cognitive or neural processing differences between the pair [ʕariis]–[ʕariif] and the pair [ʕariis]–[ʕaruus]. In contrast, on a morphemic approach to the Arabic lexicon, roots and patterns are cognitively distinct, highly abstract morphemes that play different roles in the language and where the differences in the MMN response reflect these underlying differences.

The Differential Time Course of Root and Word Pattern MMNs

The two types of standard-deviant pairs further differ with respect to the latency of the MMN peak they evoke. Specifically, the word pair differing by a word pattern shows an MMN response starting at 250 msec after the deviation point of the word, whereas the MMN response to words differing by a root consonant starts at 160 msec after deviation point. This can partly be explained by the different points in time where the standards and THE deviants diverged from each other in the two conditions (see Figure 1). However, the precedence of the root MMN compared with the word pattern MMN fits well with results from other tasks such as masked priming, which show that root priming emerges early, at an SOA of 32 msec, and remains significant throughout longer SOAs (e.g., 48, 64, and 80 msec), whereas the word pattern priming effects emerge later, at an SOA of 48 msec, and disappear at the longer SOA (Boudelaa & Marslen-Wilson, 2005; Deutsch, Frost, Pollatsek, & Rayner, 2005). Note also that despite the relative timing differences of the responses in the two conditions, both MMN peaks occur after the word recognition points established in the gating task. Together with the significant lexicality effects in both conditions, this suggests that MMN responses are sensitive to the morpholexical characteristics of the input (see Pulvermüller, Shtyrov, Ilmoniemi, & Marslen-Wilson, 2006). In both cases, the underlying morpheme has to be accessed for a lexical MMN to be generated, but the timing with which a word pattern and a root are accessed from speech can clearly be different, reflecting the contrasting distributional and structural properties of the two morphemes.

It seems unlikely that the topographic differences between root and patterns would change even if these two units could be matched on frequency of occurrence (Rugg,

1990). Roots and patterns are two morphemic entities with distinct functional properties, and as such they have different electrophysiological profiles. Previous research contrasting function and content words matched on frequency found that although the two vocabulary categories can have comparable latency profiles, their topographic profiles can be quite distinct (Pulvermüller, 2001).

Root and Word Pattern MMNs in a Wider Context

The left-lateralized MMN response in the word pattern condition bears some resemblance to the syntactic violation responses including the ELAN and the LAN response in terms of both topography and latency. These responses lateralize to the left and both are elicited some 100–300 msec after the offset of mismatching or violating information. Furthermore, the LAN response is evoked by morphosyntactic violations, whereas the word pattern MMN is elicited by changing a morpheme that carries morphosyntactic and phonological information. However, despite these parallels, it is still an open question whether the LAN and the word pattern MMN are generated by identical or overlapping neural systems. This could be assessed by looking at whether doubly mismatching stimuli like the existing [kalb] *dog* and the nonexisting form *[kalbuun], which has a different word pattern and is incorrectly inflected with the regular plural suffix ~*uun*, show parallel effects in MMN and LAN tasks.

Where the root MMN is concerned, both the topography and the time course of the response are markedly different from the N400 typically found with semantic incongruities. The root MMN has a much earlier time course since it begins to be detectable at about 150 msec after onset of the mismatching information, whereas the N400 typically emerges at around 300 msec after the onset of the incongruent item. Topographically, the root MMN exhibits a bilateral fronto-central distribution, whereas the N400 is centro-parietally distributed. These differences between the two types of negativities suggest that different cognitive processing components are involved in dealing with combinatorial morphology and combinatorial semantics, with each occurring at a different time scale and engaging different brain systems. In an MMN setting, access to the meaning of the word starts as soon as the word is heard or more precisely as soon as the word recognition point is reached (Marslen-Wilson & Welsh, 1978). By contrast, the typical setting for the emergence of an N400 response is a sentence involving a semantic violation of some sort linked to a representation of utterance meaning that has developed over time as the sentence is heard. Although comprehending a single Arabic word and comprehending a whole sentence can both involve combinatorial processes in the sense of recovering a root and a word pattern in the first case and of building an overall meaning in the second, the two combinatorial processes are markedly different and place different demands on the cognitive system.

From the perspective of a more general theory of morphological processing and representation, the present results suggest that there are identifiable neural circuits dedicated to the processing of morphology, and that these networks dissociate both topographically and temporally depending on the functional and distributional properties of the morpheme. This outcome is difficult to reconcile with the strong view that morphology merely reflects the convergence of form and meaning and does not evolve into a cognitively and neurally independent level of representation (Devlin et al., 2004; Plaut & Gonnerman, 2000; Seidenberg & Gonnerman, 2000; Joanisse & Seidenberg, 1999; Seidenberg, 1987). Although it is plausible that morphology initially emerges during language development as a consequence of correlations between form and meaning, it seems clear that the end-state lexicon does feature morphology as a distinct neurocognitive component.

The view that circuits with specific cortical distributions differentially contribute to morphology on the one hand and semantics, orthography, and phonology on the other is further supported by the many behavioral reports that document a clear dissociation between the effects of morphology and the other domains of knowledge (Longtin, Segui, & Halle, 2003; Rastle, Davis, Marslen-Wilson, & Tyler, 2000; Pulvermüller et al., 1995; Marslen-Wilson et al., 1994). This is particularly apparent in Semitic languages where morphological effects are salient when form-based and meaning-based effects either are absent or have a clearly different time course (Boudelaa & Marslen-Wilson, 2004, 2005; Frost, Kugler, Deutsch, & Forster, 2005; Frost et al., 1997).

From the neural perspective, the present results document for the first time a specific neural substrate for the Semitic root and word pattern, confirming that morphological structure does evolve into an organizing principle of the mental lexicon when the linguistic environment is propitious. In languages like Arabic and Hebrew, where morphological composition and decomposition are obligatory processes invoked during speech production and comprehension and where morphemic and semantic aspects of lexical representation seem to be strongly dissociated, the brain is most likely to assign a cognitively salient role to morphological computations and to develop discrete neural subsystems to support these.

Acknowledgments

This work was supported by the Medical Research Council UK (U.1055.04.002.00001.01).

Reprint requests should be sent to Sami Boudelaa, MRC-Cognition and Brain Sciences Unit, 15 Chaucer Road, Cambridge CB2 7EF, UK, or via e-mail: sami.boudelaa@mrc-cbu.cam.ac.uk.

Notes

1. This composite characteristic of the word pattern has motivated its fractionation by some theorists into a CV-skeleton morpheme—that is, the sequence of consonants and vowels

determining the phonological shape of the word—and a vocalic morpheme, a set of vowels conveying grammatical functions such as active, passive, and plural (McCarthy, 1981). We have found some evidence in support of this view in previous research (Boudelaa & Marslen-Wilson, 2004).

2. This was also the approximate word recognition point for these words (Grosjean, 1980; Marslen-Wilson & Welsh, 1978), as estimated by a gating task run on these stimuli.

3. The recognition point for the word pattern words, also estimated by a gating task, fell at around 350 msec, at the onset of the final consonant.

4. Although the exact relationship between off-line ratings and on-line processing is not currently well understood, it is a standard practice in the literature to use off-line ratings in ANCOVAs and Regression designs to estimate the amount of variance accounted for by various factors such as semantic relatedness (Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Rastle et al., 2000), imageability (Gennari & Poeppel, 2003), and action association (Davis et al., 2004).

REFERENCES

- Barkai, M. (1980). Aphasie evidence for lexical and phonological representations. *Afroasiatic Linguistics*, 7/6, 163–187.
- Benmamoun, E. (1998). Arabic morphology: The central role of the imperfective. *Lingua*, 108, 175–201.
- Bentin, S., Kutas, M., & Hillyard, S. A. (1995). Semantic processing and memory for attended and unattended words in dichotic listening: Behavioural and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 54–67.
- Bornkessel, I., & Schlesewsky, M. (2006). The extended argument dependency model: A neurocognitive approach to sentence comprehension across languages. *Psychological Review*, 113, 787–821.
- Boudelaa, S., & Marslen-Wilson, W. D. (2001). Morphological units in the Arabic mental lexicon. *Cognition*, 81, 65–92.
- Boudelaa, S., & Marslen-Wilson, W. D. (2004). Allomorphic variation in Arabic: Implications for lexical processing and representation. *Brain and Language*, 90, 106–116.
- Boudelaa, S., & Marslen-Wilson, W. D. (2005). Discontinuous morphology in time: Incremental masked priming in Arabic. *Language and Cognitive Processes*, 20, 207–260.
- Bozic, M., Marslen-Wilson, W. D., Stamatakis, E., Davis, M. H., & Tyler, L. K. (2007). Differentiating morphology, form and meaning: Neural correlates of morphological complexity. *Journal of Cognitive Neuroscience*, 19, 1494–1507.
- Caplan, D. (1992). *Language: Structure, processing, and disorders*. Cambridge, MA: MIT Press.
- Caramazza, A., Laudanna, A., & Romani, C. (1988). Lexical access and inflectional morphology. *Cognition*, 28, 297–332.
- Davis, M. H., Meunier, F., & Marslen-Wilson, W. D. (2004). Neural responses to morphological, syntactic, and semantic properties of single words: An fMRI study. *Brain and Language*, 89, 439–449.
- Deutsch, A., Frost, R., Pollatsek, A., & Rayner, K. (2005). Morphological parafoveal preview benefit effects in reading: Evidence from Hebrew. *Language and Cognitive Processes*, 20, 341–371.
- Devlin, J. T., Jamison, H. L., Matthews, P. M., & Gonnerman, L. M. (2004). Morphology and the internal structure of words. *Proceedings of the National Academy of Sciences, U.S.A.*, 1–5.

- Friederici, A. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, 6, 78–84.
- Frost, R., Deutsch, A., & Forster, K. I. (2000). Decomposing morphologically complex words in a nonlinear morphology. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26, 751–765.
- Frost, R., Deutsch, A., Gilboa, O., Tannenbaum, M., & Marslen-Wilson, W. D. (2000). Morphological priming: Dissociation of phonological, semantic, and morphological factors. *Memory & Cognition*, 1277–1288.
- Frost, R., Forster, K. I., & Deutsch, A. (1997). What can we learn from the morphology of Hebrew: A masked priming investigation of morphological representation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 23, 829–856.
- Frost, R., Kugler, T., Deutsch, A., & Forster, K. I. (2005). Orthographic structure versus morphological structure: Principles of lexical organization in a given language. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 31, 1293–1326.
- Gafos, I. A. (2003). Greenberg's asymmetry in Arabic: A consequence of stems in paradigms. *Language*, 79, 317–355.
- Gennari, S., & Poeppel, D. (2003). Processing correlates of lexical semantic complexity. *Cognition*, 89, B27–B41.
- Geschwind, N. (1970). The organisation of language and the brain. *Science*, 170, 940–944.
- Grosjean, F. (1980). Spoken word recognition processes and the gating paradigm. *Perception & Psychophysics*, 82, 267–283.
- Hauk, O. (2004). Keep it simple: A case for using classical minimum norm estimates in the analysis of EEG and MEG data. *Neuroimage*, 21, 1612–1621.
- Hauk, O., Davis, M. H., Ford, M., Pulvermüller, F., & Marslen-Wilson, W. D. (2006). The time course of visual word recognition as revealed by linear regression analysis of ERP data. *Neuroimage*, 30, 1383–1400.
- Heath, J. (2002). Arabic derivational ablaut, processing strategies, and consonantal “roots.” In J. Shimron (Ed.), *Language processing and acquisition in languages of Semitic root-based morphology*. Amsterdam: John Benjamins.
- Holes, C. (1995). *Modern Arabic*. London: Longman.
- Joanisse, M., & Seidenberg, M. (1999). Impairments in verb morphology following brain injury: A connectionist model. *Proceedings of the National Academy of Sciences, U.S.A.*, 1–6.
- Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, 207, 203–205.
- Kutas, M., & Hillyard, S. A. (1984). Brain potentials reflect semantic incongruity. *Nature*, 307, 161–163.
- Longtin, C. M., Segui, J., & Halle, P. A. (2003). Morphological priming without morphological relationship. *Language and Cognitive Processes*, 18, 313–334.
- Lück, M., Hanhne, A., & Clahsen, H. (2006). Brain potentials to morphologically complex words during listening. *Brain Research*, 1077, 144–152.
- Marangolo, P., Piras, F., Galati, G., & Burani, C. (2004). The neural substrates of derivational morphological processing: An fMRI study. *Cortex*, 40, 185–186.
- Marslen-Wilson, W. D., & Tyler, L. K. (1997). Dissociating types of mental computation. *Nature*, 387, 592–594.
- Marslen-Wilson, W. D., & Tyler, L. K. (2007). Morphology, language and the brain: The decompositional substrate for language comprehension. *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences*, 362, 823–836.
- Marslen-Wilson, W. D., Tyler, L. K., Waksler, R., & Older, L. (1994). Morphology and meaning in the English mental lexicon. *Psychological Review*, 101, 3–33.
- Marslen-Wilson, W. D., & Welsh, A. (1978). Processing interactions during word recognition in continuous speech. *Cognitive Psychology*, 10, 29–63.
- McCarthy, G., & Nobre, A. C. (1993). Modulation of semantic processing by spatial selective attention. *Electroencephalography and Clinical Neurophysiology*, 88, 227–234.
- McCarthy, J. J. (1981). A prosodic theory of non-concatenative morphology. *Linguistic Inquiry*, 12, 373–418.
- McCarthy, J. J. (1982). Prosodic templates, morphemic templates, and morphemic tiers. In H. Van der Hulst & N. Smith (Eds.), *The structure of phonological representations* (pp. 191–223). Dordrecht: Foris Publications.
- McKinnon, R., Allen, M., & Osterhout, L. (2003). Morphological decomposition involving non-productive morphemes: ERP evidence. *NeuroReport*, 14, 883–886.
- Mohr, B., Pulvermüller, F., & Zaidel, E. (1994). Lexical decision after left, right and bilateral presentation of content words, function words and non-words: Evidence for interhemispheric interaction. *Neuropsychologia*, 32, 105–124.
- Näätänen, R. (1995). The mismatch negativity: A powerful tool for cognitive neuroscience. *Ear and Hearing*, 16, 6–18.
- Näätänen, R. (2001). The perception of speech sounds by the humans brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology*, 38, 1–21.
- Näätänen, R., & Alho, K. (1997). Mismatch negativity-The measure for central sound representation accuracy. *Audiology and Neurootology*, 2, 341–353.
- Neville, H., Mills, D., & Lawson, D. (1992). Fractionating language: Different neural subsystems with different sensitive periods. *Cerebral Cortex*, 2, 244–258.
- Neville, H., Nicol, J., Barss, A., Forster, K., & Garrett, M. (1991). Syntactically based sentence processing classes: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*, 3, 155–170.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia*, 9, 97–113.
- Penolazzi, B., Hauk, O., & Pulvermüller, F. (2007). Early semantic context integration and lexical access as revealed by event-related potentials. *Biological Psychology*, 74, 374–388.
- Plaut, D., & Gonnerman, L. M. (2000). Are non-semantic morphological effects incompatible with a distributed connectionist approach to lexical processing? *Language and Cognitive Processes*, 15, 445–485.
- Prunet, J. F., Béland, R., & Idrissi, A. (2000). The mental representation of Semitic words. *Linguistic Inquiry*, 31, 609–648.
- Pulvermüller, F. (2001). Imaging language in the brain. In D. Amit (Ed.), *Frontiers in neurobiology. An international handbook: Volume 5. Intelligence systems*. Rome: Encyclopaedia Italiana Press.
- Pulvermüller, F., Lutzenberger, W., & Birbaumer, N. (1995). Electrocortical distinction of vocabulary types. *Electroencephalography and Clinical Neurophysiology*, 94, 357–370.
- Pulvermüller, F., & Shtyrov, Y. (2003). Automatic processing of grammar in the human brain as revealed by the mismatch negativity. *Neuroimage*, 20, 159–172.
- Pulvermüller, F., & Shtyrov, Y. (2006). Language outside the focus of attention: The mismatch negativity as a tool for studying higher cognitive processes. *Progress in Neurobiology*, 79, 49–71.

- Pulvermüller, F., Shtyrov, Y., Hasting, A. S., & Carlyon, R. B. (2008). Syntax as a reflex: Neurophysiological evidence for early automaticity of grammatical processing. *Brain & Language, 104*, 244–253.
- Pulvermüller, F., Shtyrov, Y., Ilmoniemi, R., & Marslen-Wilson, W. D. (2006). Tracking speech comprehension in space and time. *Neuroimage, 31*, 1297–1305.
- Pulvermüller, F., Shtyrov, Y., Kujala, T., & Näätänen, R. (2004). Word specific cortical activity as revealed by the mismatch negativity. *Psychophysiology, 41*, 106–112.
- Rastle, K., Davis, M. H., Marslen-Wilson, W. D., & Tyler, L. K. (2000). Morphological and semantic effects in visual word recognition: A time-course study. *Language and Cognitive Processes, 15*, 507–537.
- Ratcliffe, R. R. (2004). Sonority-based parsing at the margins of Arabic morphology: In response to Prunet, Beland and Idrissi (2000) and Davis and Zawaydeh (1999, 2001). *Al-Arabiyya, 37*, 73–95.
- Rueckl, J. G., Mikolinski, M., Raveh, M., Miner, C. S., & Mars, F. (1997). Morphological priming, fragment completion, and connectionist networks. *Journal of Memory and Language, 36*, 382–405.
- Rugg, M. D. (1990). Event-related potentials dissociate repetition effects of high and low frequency words. *Memory & Cognition, 18*, 367–379.
- Schreuder, R., & Baayen, R. H. (1995). Modelling morphological processing. In L. B. Feldman (Ed.), *Morphological aspects of language processing* (pp. 131–154). Hillsdale, NJ: Erlbaum.
- Seidenberg, M. (1987). Sublexical structure in visual word recognition: Access units or orthographic redundancy? In M. Coltheart (Ed.), *Attention and performance XII* (pp. 244–263). Hillsdale, NJ: Lawrence Erlbaum.
- Seidenberg, M., & Gonnerman, L. M. (2000). Explaining derivational morphology as the convergence of code. *Trends in Cognitive Sciences, 4*, 353–361.
- Shtyrov, Y., & Pulvermüller, F. (2002). Memory traces for inflectional affixes as shown by the mismatch negativity. *European Journal of Neuroscience, 15*, 1085–1091.
- Taft, M. (1979). Recognition of affixed words and the word frequency effect. *Memory and Cognition, 7*, 263–272.
- Tyler, L. K., Marslen-Wilson, W. D., & Stamatakis, E. A. (2005). Differentiating lexical form, meaning, and structure in the neural language system. *Proceedings of the National Academy of Sciences, U.S.A., 102*, 8375–8380.
- Tyler, L. K., Stamatakis, E. A., Post, B., Randall, B., & Marslen-Wilson, W. D. (2005). Temporal and frontal systems in speech comprehension: An fMRI study of past tense processing. *Neuropsychologia, 43*, 1963–1974.
- Vannest, J., Polk, T. A., & Lewis, R. L. (2005). Dual-route processing of complex words: New fMRI evidence from derivational suffixation. *Cognitive, Affective & Behavioral Neuroscience, 5*, 67–76.
- Versteegh, K. (1997). *The Arabic language*. Edinburgh: Edinburgh University Press.
- Weyerts, H., Penke, M., Dohrn, U., Clahsen, H., & Müte, T. F. (1997). Brain potentials indicate differences between regular and irregular German plurals. *NeuroReport, 8*, 957–962.
- Wright, W. (1995). *A grammar of the Arabic language*. Cambridge, MA: Cambridge University Press.