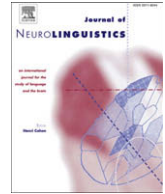




Contents lists available at ScienceDirect

Journal of Neurolinguistics

journal homepage: www.elsevier.com/locate/jneuroling



Language-specific activations in the brain: Evidence from inflectional processing in bilinguals

Minna Lehtonen^{a,b,c,*}, Victor Vorobyev^c, Anna Soveri^{b,c}, Kenneth Hugdahl^d,
Terhi Tuokkola^{e,f}, Matti Laine^{b,c}

^a Helsinki Collegium for Advanced Studies, P.O. Box 4, FIN-00014, University of Helsinki, Finland

^b Department of Psychology, Åbo Akademi University, Finland

^c Centre for Cognitive Neuroscience, University of Turku, Finland

^d Department of Biological and Medical Psychology, University of Bergen, Norway

^e Medical Imaging Centre of Southwest Finland, Finland

^f Department of Radiology, University of Turku, Finland

ARTICLE INFO

Article history:

Received 26 November 2008

Received in revised form 7 April 2009

Accepted 10 May 2009

Keywords:

Inflectional processing

Brain imaging

fMRI

Bilinguals

ABSTRACT

We investigated the neural correlates of morphological processing in two structurally different languages within the same individuals. An interesting contrast is provided by Finnish and Swedish where most inflected Finnish nouns tend to show a processing cost (i.e., longer reaction times and higher error rates) compared to monomorphemic nouns, while most inflected Swedish nouns do not show such a cost. This has been taken as evidence for morphological decomposition in Finnish and full-form recognition of inflected nouns in Swedish. While most previous imaging studies had studied the two morphological processing routes (decomposition and storage) within the same language and often by comparing regular vs. irregular forms, we employed a cross-language setting and a direct contrast between morphologically complex vs. simple words. We subjected high-proficient Finnish–Swedish early bilinguals to a visual lexical decision task with inflected vs. monomorphemic Finnish and Swedish nouns while measuring their brain activation by fMRI. The participants showed an inflectional processing cost and related left fronto-temporal activation increases in Finnish but not in Swedish. This suggests a language-specific processing difference in the brain, possibly reflecting the structural difference between these two languages.

* Corresponding author. Helsinki Collegium for Advanced Studies, P.O. Box 4, FIN-00014, University of Helsinki, Finland.
Fax: +358 9 191 24509.

E-mail address: minna.h.lehtonen@helsinki.fi (M. Lehtonen).

In addition, the activations appeared in regions related to lexical-semantic and syntactic processing rather than visual word form processing. This is in line with previous studies in Finnish, suggesting that the morphological processing cost stems primarily from the later, semantic-syntactic stage.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

The recognition of morphologically complex words (e.g., HOUSE + S) has been an active research topic in psycho- and neurolinguistics for many years. Models of morphological processing have varied from assuming that all morphologically complex words are decomposed into their constituents during recognition (e.g., Stockall & Marantz, 2006; Taft, 1979) to postulating recognition via full forms for all words (Butterworth, 1983). Some models, in turn, assume that both of these recognition “routes” can be employed (e.g., Niemi, Laine, & Tuominen, 1994; Schreuder & Baayen, 1995), but the specific route successful for each word may depend on various factors, such as word frequency, the relative frequency between the whole word and its base (Hay, 2001), word formation type (e.g., derivation vs. inflection), or semantic transparency, to name a few. The main aim of the present study is to investigate whether language structure might affect the recognition route used with inflected words and hence whether different brain activations are seen for morphological processing in two structurally different languages, Finnish and Swedish. The framework adopted in the present study is thus a dual-route view on morphological processing, and the neural correlates of these two assumed routes are investigated in a cross-language setting. Early bilingual participants with very high proficiency in both languages provide a powerful testing ground for the effects between languages, allowing us to investigate the processing of two different languages within the same brain, by a within-subjects design.

There is empirical behavioral evidence suggesting that in languages like English or Dutch, full-form recognition may be the predominant route used for inflected words (Baayen, Dijkstra, & Schreuder, 1997; Sereno & Jongman, 1997). It is, however, possible that languages with a richer morphological structure show more evidence of decomposition. Behavioral studies investigating morphological processing in two structurally different languages, Finnish and Swedish, suggest that language structure may indeed play a role in how inflected words of each language are represented. Finnish is a non-Indo-European, Finno-Ugric agglutinative language with an enormous amount of possible inflected word forms, while Swedish is an Indo-European, Germanic language with a more modest number of possible inflected word forms. Due to this difference, it is reasonable to speculate that processing of morphologically complex words might differ between these two languages. Because of the immense number of possible word forms in Finnish, it is plausible that most Finnish inflected words are not listed as a whole in the mental lexicon. Indeed, an inflectional processing cost (longer reaction times (RTs) and/or higher error rates for inflected than for monomorphemic nouns) is a robust finding in studies on Finnish nouns and has been observed in the standard visual lexical decision task (Laine & Koivisto, 1998; Laine, Vainio, & Hyönä, 1999; Niemi et al., 1994), progressive demasking (Laine, Vainio, et al., 1999), eye-movement recordings (Hyönä, Laine, & Niemi, 1995), auditory lexical decision (Leinonen et al., 2009) as well as in the reading-aloud performance in aphasic patients (Laine, Niemi, Koivuselkä-Sallinen, Ahlsén, & Hyönä, 1994; Laine, Niemi, Koivuselkä-Sallinen, & Hyönä, 1995). These studies can be interpreted as support for the assumption that most Finnish inflected words are decomposed into stem and affix during recognition.¹

In Swedish, on the other hand, full-form recognition could be a possible alternative for many inflected word forms (Ahlsén, 1994). Lehtonen and Laine (2003) and Lehtonen, Niska, Wande, Niemi,

¹ Connectionist models of morphological processing might, in principle, also account for these findings, but we are not aware of any connectionist implementation that would account for the kind of reaction time difference presented here. Accordingly, the present paper is based on a decompositional framework.

and Laine (2006) used the visual lexical decision task and systematically investigated the recognition of inflected vs. monomorphemic nouns in Finnish and Swedish native monolinguals as well as in Finnish–Swedish bilinguals who had acquired both of these languages in early childhood and had used them actively since then. In these studies, the presence of a processing cost between inflected vs. monomorphemic words in visual lexical decision was interpreted as reflecting decomposition, and similar RTs and error rates for these word groups as reflecting full-form processing. These studies demonstrated that during visual recognition, most Finnish inflected nouns showed a processing cost relative to corresponding monomorphemic words and were thus assumedly decomposed into stem and suffix during recognition. On the other hand, most Swedish inflected nouns did not show a processing cost, and they were thus interpreted to be recognized as full forms. This general pattern was observed in both monolinguals and early bilinguals. However, it was modulated by word frequency.

It has been suggested that high frequency inflected words are more likely to develop full-form representations than low frequency ones (e.g., Alegre & Gordon, 1999; Baayen et al., 1997; Schreuder & Baayen, 1995). The studies of Lehtonen and Laine (2003) and Lehtonen, Niska, et al. (2006) included three contrasts between inflected vs. monomorphemic words taken from different frequency ranges: high, medium, and low. While a processing cost was observed in the low and in the medium frequency range in Finnish, the high frequency inflected words in Finnish did not show a processing cost in Finnish monolinguals, suggesting that they had been encountered so often that they had developed full-form representations. In Swedish, there was no processing cost for the high and the medium frequency ranges, but for the low frequency Swedish inflected words a processing cost was observed, suggesting that these rarely encountered forms were decomposed. In sum, it was concluded that both routes are in use in both languages, but the main route used is different, presumably because of the structural difference between these two languages. The bilingual groups of each study showed otherwise similar effects to those of the monolinguals, but also a slightly stronger tendency for decomposition in comparison to monolinguals, especially in the Finnish study where they showed a processing cost in all frequency ranges, even in the high one. This difference was interpreted to reflect less exposure to word forms for the balanced bilinguals: employing two languages to an approximately similar extent in their everyday lives, they receive on average much less input per language than monolinguals. This would have resulted in lower rates of full-form representations for inflected word forms than in monolinguals. The frequency ranges where these early balanced bilinguals showed differential effects of morphological processing across the two languages were thus the medium and high frequency range where decomposition in Finnish and full-form processing in Swedish were observed.

The present study investigates whether neural evidence for differential representation of inflected words in two structurally different languages can be found within the same individuals. More specifically, we study whether brain activation patterns for visual word recognition differ between Finnish vs. Swedish medium-to-high frequency inflected words in Finnish–Swedish early bilinguals. Given the behavioral evidence reviewed above, we would expect this to be the case, as morphological decomposition and full-form processing represent qualitatively different operations. Assuming that full-form storage of inflected words entails whole-word representations at both word form and semantic-syntactic levels, such words should be accessed in the same fashion as monomorphemic words, and thus share the same neural substrates. Morphological decomposition of inflected words, on the other hand, should call for additional neural resources, related to morpheme-based visual word form processing and/or on-line semantic-syntactic integration of the constituents to arrive at the meaning of an inflected word (Laine et al., 1994).

The previous brain imaging studies on morphological processing using PET or fMRI have used a variety of tasks ranging, e.g., from production of morphologically complex forms (e.g., Beretta et al., 2003; Desai, Conant, Waldron, & Binder, 2006; Jaeger et al., 1996; Joanisse & Seidenberg, 2005; Marangola, Piras, Galati, & Burani, 2006; Sahin, Pinker, & Halgren, 2006) and making same-different judgments on auditory stimuli (Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005) to making visual lexical decisions on inflected vs. unmarked words (Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006; Yokoyama et al., 2006) and to memory encoding of morphologically complex words (Laine, Rinne, Krause, Teräs, & Sipilä, 1999; Vannest, Polk, & Lewis, 2005). Most studies have been conducted in English (Davis, Meunier, & Marslen-Wilson, 2004; Desai et al., 2006; Devlin, Jamison,

Matthews, & Gonnerman, 2004; Jaeger et al., 1996; Tyler et al., 2005; Vannest et al., 2005), but also studies in German (Beretta et al., 2003; Sach, Seitz, & Indefrey, 2004), Finnish (Laine, Rinne, et al., 1999; Lehtonen, Vorobyev, et al., 2006), and Hebrew (Bick, Goelman, & Frost, 2008; Palti, Ben Shachar, Hendler, & Hadar, 2007), as well as single studies in Italian (Marangolo et al., 2006) and Japanese (Yokoyama et al., 2006) have been reported. Even though the specific activation patterns have differed across studies and especially in those concerning production, the most consistently activated region for morphological processing has been the left inferior frontal cortex. The involvement of the left posterior temporal areas has also often been found, particularly in receptive tasks (see the review in Lehtonen, Vorobyev, et al., 2006). These two areas have been found to be central in reading and lexical processing also more generally (e.g., Jobard, Crivello, & Tzourio-Mazoyer, 2003).

Most previous imaging studies investigating morphological processing have focused on two processing “routes”, storage and decomposition, but the main emphasis has been on the contrast between processing of irregularly (e.g., RUN – RAN) and regularly (e.g., JUMP – JUMPED) inflected words. Many of these researchers (Beretta et al., 2003; Jaeger et al., 1996; Sach et al., 2004; Tyler et al., 2005; Vannest et al., 2005) have taken as a starting point the assumption that regular words are computed by a rule and irregular words are stored as full forms in the mental lexicon. These assumed processing differences thus resemble the full-form route and the decomposition route of the parallel dual-route models. Most of these brain imaging studies have employed production of past tense forms from the stem as their task and often unexpectedly reported stronger activations for the irregular (storage) than regular (computation) words. However, producing an irregular past tense form from a stem may, in addition to the retrieval of the whole form, require the inhibition of applying the regular inflectional rule. Therefore it may include extra processing relative to the processing of monomorphemic words, even though they are both assumedly stored as whole units. In contrast, in a receptive task, such as in the same-different judgment of auditorily presented regularly or irregularly inflected English words (Tyler et al., 2005), regulars elicited greater activation than irregulars in the left inferior frontal cortex and in left superior temporal areas. These activations were suggested to reflect automatic segmentation of morphological affixes and access to the stems, respectively.

The auditory modality differs from the visual one in that the presentation of the stem and the suffix are temporally distinct, successive, while in the visual modality both parts are usually registered simultaneously, in parallel, at least in the case of short words. Thus, in the auditory domain, the stem is likely to get a head-start in the processing, which may make the decomposition route more likely to win the race. In the visual domain, on the other hand, the full-form route may end up being the primary route that wins in most cases in a morphologically limited language like English. The study by Davis et al. (2004), for instance, found no differences between morphologically complex (regularly inflected and derived) and simple English words in a visual receptive task. Vannest et al. (2005), in turn, observed stronger effects for assumedly decomposable (regularly inflected and derived) English words, but the task was memory encoding, which, in principle, may include post-lexical analytical processes for morphologically complex words relative to monomorphemic words. Recently, an fMRI study combining masked priming with brain imaging (Gold & Rastle, 2007) found specifically morphological effects in the left occipito-temporal cortex that indicate that the decomposition route is activated initially for all, even only apparently morphologically complex words. However, it is important to note that such masked priming results do not exclude the possibility that it is the full-form route that in normal circumstances most often wins the race in English language processing.

Using Japanese, an agglutinative language, Yokoyama et al. (2006) in turn showed that visual lexical decisions to inflected passive verb forms elicited stronger left inferior frontal activation than unmarked less complex active forms. Brain imaging in Finnish also suggests that decomposition is the prevailing processing route in that language, as implicated by the behavioral studies reviewed above. Lehtonen, Vorobyev, et al. (2006), using visual lexical decision and fMRI, found greater activation for inflected than monomorphemic visually presented Finnish words in the left inferior frontal and left superior temporal areas. The same areas were activated in the study by Laine, Rinne, et al. (1999) who found increased activation for inflected vs. monomorphemic Finnish words, albeit with an auditory memory encoding task and PET. Lehtonen, Vorobyev, et al. (2006) focused on the decomposition process in more detail and studied the functional locus of the morphological processing cost (i.e., the longer RTs and higher error rates for inflected than monomorphemic nouns in Finnish, see above). Following models

of morphological processing, they hypothesized that the processing cost could stem from 1) the segmentation of the morphological constituents at the visual word form level and/or from 2) accessing the decomposed amodal representations of the constituents and integrating their meaning at the later, semantic-syntactic level (see, e.g., Laine et al., 1994; Schreuder & Baayen, 1995, for discussion about the levels involved in morphological processing). On the basis of meta-analyses and reviews on lexical processing, especially with regard to reading or visual word recognition, they made neuroanatomical predictions as to which areas would correspond to each of the two stages, namely visual word form processing, and lexical-semantic/syntactic processing. These same regions are employed in the analyses of the present study.

The left inferior occipito-temporal cortex has been repeatedly observed to be sensitive to visual word form processing (Jobard et al., 2003; McCandliss, Cohen, & Dehaene, 2003), showing, e.g., more activation for words than for consonant strings and being insensitive to semantic aspects of words (Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002). The specificity of this area for language has, however, been debated, and Jobard et al. (2003) note that it seems to be responsible for other types of complex visual processing as well. According to them, it may be involved in prelexical segmentation and classification of all word-like stimuli. With regard to morphology, the left occipito-temporal area has been sensitive to orthographically and morphologically related words in masked priming tasks (Devlin et al., 2004; Gold & Rastle, 2007) which are assumed to emphasize early levels of word recognition. It appears therefore likely that this area would be activated when demands at the visual word form level increase due to decomposition, i.e., segmentation of the word form into a stem and an affix. Relevant to the later stage of morphological decomposition, areas that have been associated to semantic processing, e.g., during word reading, include the ventral parts (triangular and orbital) of the left inferior frontal cortex (Démonet, Thierry, & Cardebat, 2005; Jobard et al., 2003) and the posterior parts of the middle and superior temporal gyri (Fiez & Petersen, 1998; Jobard et al., 2003). Syntactic aspects of words and sentences have, in turn, been found to activate the more dorsal parts of the left inferior frontal gyrus (BA 44/45) and the posterior superior temporal areas (Démonet et al., 2005; Friederici, Opitz, & von Cramon, 2000; Grodzinsky & Friederici, 2006; Vigneau et al., 2006).

When focusing on these regions, Lehtonen, Vorobyev, et al. (2006) found that the contrast between the recognition of inflected vs. monomorphemic Finnish nouns elicited increased activation mainly in the left inferior frontal gyrus (BA 47) and the left posterior temporal area (BA 22/21/39). These areas have been related to lexical-semantic or syntactic aspects, rather than visual word form processing. On the other hand, activation in the left occipito-temporal cortex (BA 37/19), an area previously associated with visual word form processing, was less clear. This suggests that the morphological processing cost would primarily stem from the semantic-syntactic stage where the meaning and syntactic aspects of the morphemic constituents are accessed and integrated. Findings supporting this view were also found in a recent ERP study (Lehtonen et al., 2007) and in an earlier behavioral study by Hyönä, Vainio, and Laine (2002). These findings do not exclude the possibility that early decomposition takes place in Finnish,² but it may be too automatic to contribute much to the processing cost and the current methods are perhaps not sensitive enough to catch it.

In sum, the present study investigated the two assumed routes of morphological processing, storage and decomposition, in a cross-language setup. We were interested in seeing whether differential effects would be observed for visual recognition of inflected words in two structurally different languages. By testing early, high-proficient Finnish–Swedish bilinguals we were able to investigate the brain activation patterns in the two languages within the same individuals. On the basis of earlier behavioral studies (Lehtonen & Laine, 2003; Lehtonen, Niska, et al., 2006) we expected there to be increased activation for Finnish inflected words when compared to corresponding monomorphemic words, but not for Swedish which would show evidence of full-form processing, i.e., similar activations for inflected and monomorphemic words. On the basis of those behavioral findings as well as general brain imaging results on early bilinguals (see, e.g., the review by Abutalebi & Green, 2007), we expected

² Some models of morphological processing (e.g., the supralexical model, Giraudo & Grainger, 2000, 2001) have suggested that decomposition takes place only at the later, amodal level of processing, after accessing full-form representations at form level. This model is also able to explain the late morphological effect.

these early bilinguals not to differ qualitatively from monolingual speakers of each language. There are currently no imaging studies conducted on morphological processing in Swedish, but with regard to Finnish, there is a corresponding study in Finnish monolinguals (Lehtonen, Vorobyev, et al., 2006) that can be compared with the present one. In order to make these two studies comparable, we used the same experimental setup and task and, after performing whole-brain analyses, focused on the same volumes of interest as in that study. We were also interested in seeing whether we could replicate the finding by Lehtonen, Vorobyev, et al. (2006) that the morphological processing cost elicits activation increases in areas linked to the later stage of decomposition (lexical-semantic access and integration: the left posterior middle and superior temporal area, LPTA, and/or the left inferior frontal gyrus, LIFG), rather than in areas associated with early visual word form processing (the left occipito-temporal cortex, LOTC).

2. Materials and methods

2.1. Participants

Sixteen right-handed university students (mean age, 26.3 years; SD, 3.42; eight females) participated in the experiment after giving their written, informed consent. No signs of structural abnormality were observed in a screening done by a certified radiologist in the high-resolution MRI anatomical images. The study was approved by the joint Ethical Committee of the Turku University Central Hospital and the University of Turku. All of the participants had acquired both Finnish and Swedish in early childhood before starting school (i.e., before the age of seven) either at home or in daycare, and had continued using both languages up to the time of testing. The estimated mean age of acquisition for Finnish (mean, 1.96 years; SD, 1.16) did not differ significantly from that for Swedish (mean, 2.26 years; SD, 1.77; $t < 1$). They assessed their language skills in speaking, reading, speech comprehension and writing with a 7-point scale from 0 to 6 (0 = no skills in the language; 6 = excellent skills in the language, comparable to a native level). Although many of the participants reported having used somewhat more Swedish than Finnish during the past three years, the ratings showed that the participants considered their Finnish skills to be approximately equivalent to their Swedish skills in speech comprehension, reading, writing and speaking (see Table 1 for means; there were no statistically significant differences between languages in the Wilcoxon Signed Ranks Test: speaking, $Z = 1.90$, $p = 0.058$; reading and speech comprehension, equal values; writing, $Z = 1.81$, $p = 0.070$). The participants' language skills thus appeared to be rather balanced, albeit perhaps slightly stronger in Swedish, and at a very high level for the two languages studied. For more detailed information about the participants' language background and language skill estimates, see Table 1.

2.2. Materials

Two 85-item lists of real words were collected for each language, consisting of either inflected or monomorphemic nouns. The Finnish lists were collected from the unpublished Turun Sanomat lexical corpus (including 22.7 million word tokens) and the Swedish lists from the Göteborgs-Posten lexical database (including 24.2 million word tokens), using a computerized search program (Laine & Virtanen, 1999). The four lists were matched for average word length in letters (Finnish, mean 5.79 for monomorphemic, mean 5.98 for inflected words; for Swedish, mean 5.89 for monomorphemic, mean 5.91 for inflected words), surface frequency (Finnish, mean 38.6 per million for monomorphemic, mean 37.6 per million for inflected words; for Swedish, mean 41.2 per million for monomorphemic, mean 41.0 per million for inflected words) and cumulative stem frequency (Finnish, mean 152 per million for monomorphemic, mean 168 per million for inflected words; for Swedish, mean 134 per million for monomorphemic, mean 160 per million for inflected words). None of the comparisons (inflected vs. monomorphemic within languages, or corresponding word lists across languages) with the above mentioned factors yielded statistically significant differences in two-tailed t -tests. The words were collected from a medium-to-high frequency range (with surface frequencies varying from 12 per million to 141 per million) to ensure that behavioral differences would be observed between Finnish and Swedish (see Lehtonen & Laine, 2003; Lehtonen, Niska, et al., 2006). The majority (74%) of the

Table 1

Participants' language background information and self-evaluation of language skills.

Language background				
First language acquired	Finnish 31.25%	Swedish 37.5%	Both 31.25%	
Language environment during early childhood	Mother: Swedish, father: Finnish	Mother: Finnish, father: Swedish	Both parents: Finnish, Swedish outside home	Both parents: Swedish, Finnish outside home
	37.5%	12.5%	18.75%	31.25%
Language of schooling (at 7–18 years of age)	Finnish	Swedish	Swedish and partly other languages ^a	
	6.25%	87.5%	6.25%	
Current language use				
Proportion of reading in a given language in recent years (mean across participants, total 100%)	Finnish 36%	Swedish 46%	Other languages 18%	
Proportion of languages used at home, university and work (mean across participants, total 100%)	Finnish 33%	Swedish 60%	Other languages 7%	
Self-evaluation of language skills (mean for each language; scale 0–6; ranges are given in brackets)				
Domain	Finnish	Swedish	First other language	Second other language
Speaking	5.4 (4–6)	5.8 (5–6)	4.5 (3–5)	2.3 (0–4)
Speech comprehension	5.9 (5–6)	5.9 (5–6)	5.1 (4–6)	2.5 (0–5)
Reading	5.8 (5–6)	5.8 (5–6)	4.9 (3–6)	2.3 (0–4)
Writing	4.9 (3–6)	5.4 (3–6)	4.1 (3–5)	1.8 (0–3)

^a One participant reported attending school in Swedish and English during the early years of comprehensive school and in Swedish and Spanish in upper secondary school.

Finnish inflected words included a genitive ending, and locative case endings (inessive, $n = 4$; illative, $n = 10$; adessive, $n = 6$; ablative, $n = 1$; and allative, $n = 1$) were used with the rest of the items (26%). In Swedish, the majority (60%) of the inflected words were in definite utrum form, and the remaining ones (40%) had a definite neutrum ending. The words in the inflected lists were regularly inflected.³ In addition to real words, two similar groups of pseudowords were collected for each language, one consisting of purely “monomorphemic” pseudowords without any real morphemes of the language, and the other list consisting of “inflected” pseudowords which included a pseudoword stem and a real noun suffix in the language (in the Finnish part, e.g., *kapsuun*, which could be analyzed as a pseudoword noun stem *kapsu + illative case ending signaling ‘into’; and in the Swedish part, e.g., *krivan* = *kriva + definite ending -n). The pseudoword groups were constructed by changing 1–3 letters of existing words in the language in question so that they followed the phonotactic rules of the language. The inflected vs. monomorphemic pseudoword groups were matched within language, across language and across stimulus type (real words vs. pseudowords) for average word length in letters (Finnish, mean 5.86 for monomorphemic, mean 5.95 for inflected pseudowords; for Swedish, mean 5.98 for monomorphemic, mean 5.92 for inflected pseudowords). The distribution of different inflectional endings in inflected pseudowords followed that of the real word groups in each language.

2.3. Procedure

The experiment consisted of two parts, a Finnish one and a Swedish one, between which the participants had a break and came out of the scanner. One could have employed alternating runs in Swedish vs. Finnish for each subject, but we decided against that because rapid switching between languages could as such affect the results. Instead, we lumped the language-specific runs together and had a pause in-between to enable some rest. In addition, the order of the parts was counterbalanced across participants. Before each part, the participant received written instructions and a practice session of the task in the language used in that part. Similarly, the language the bilingual experimenter used with the participant at any given time was consistent with the language of the current part.

The task in both parts was the standard visual lexical decision where a letter string is shown in the middle of the screen (here written in black on a white background with capital letters) and the participant was to decide whether it is a real word in a certain language or not, and to press a corresponding button as quickly as possible. The stimuli were programmed and presented by using the Presentation software (version 9.10, Neurobehavioral Systems Inc., USA). The same software was used to synchronize stimulation with MRI image acquisition and to record the subjects’ reactions. The stimuli were projected onto a screen that the participants saw through an angled mirror fixated on the head coil. The setup of each trial was the following: an asterisk lasting for 500 ms appeared in the middle of the screen, then it disappeared for another 500 ms, after which a stimulus word was presented. The maximum time for the participants to respond was 2000 ms, but if they gave their response earlier, the word would disappear to notify that the response had been registered, thus preventing the participant from repeating button presses.

In order to gain statistical power to detect possible effects, we employed a blocked design where each of the two language parts consisted of 34 task blocks (30 seconds each) alternating with 20 s blocks of passive baseline (the REST condition) with central gaze fixation and no stimulation. Half of the task blocks consisted of only monomorphemic items (both words and pseudowords were monomorphemic) forming the MM condition; the other half consisted of only inflected items (both words and pseudowords were inflected) and constituted the INFL condition. Each task block included 10 items, 5 of which were pseudowords. Half of the participants started the block sequence with a MM stimulus block while the other half began with an INFL block. The type of stimulus (MM or INFL) changed after each task block. Otherwise the order of the task blocks was randomized for each participant. Each part of the fMRI experiment took about 28 min, in addition to the anatomical scan.

³ However, one word in the inflected Swedish list can be seen as slightly irregular.

The MRI data were collected at the PET Centre, University of Turku, Finland, by a 1.5 T Philips Gyroscan Intera scanner equipped with a standard head coil with a mirror system. Functional MRI data for each participant were obtained in ten sessions (scanner runs) each including 102 blood oxygen level-dependent (BOLD) T2*-weighted single-shot echo-planar (EPI) volume measurements (TR = 3 s, TE = 50 ms, FA = 90°, slice thickness = 4 mm, interslice gap = 0.4 mm, FOV = 192 mm, matrix = 64 × 64). Each volume measurement (image) consisted of 30 axial slices covering the brain, including most of the cerebellum. In order to minimize eye-movement artifacts, eye areas were excluded from the image area by proper orientation of the slices. Each session started with four dummy scans with no data acquisition to allow for T1 stabilization. Prior to the functional scanning, a high-resolution 3D T1-weighted anatomical image (TR = 25 ms, TE = 4.6 ms, flip angle = 30°, voxel size = 1.09 × 1.09 × 0.5 mm, matrix size = 256 × 256, FOV = 27.9 cm²) was acquired for each participant.

2.3.1. fMRI analysis

Image preprocessing and first-level fixed-effect statistical analyses were carried out using the Statistical Parametric Mapping software (SPM2, Frackowiak et al., 2004, Wellcome Dept. of Cognitive Neurology, London, UK) running under Matlab 6.0 (Mathworks Inc., USA). EPI images were realigned to the first one in the first session in order to minimize motion-induced artifacts. Then the high-resolution anatomical image was coregistered to the position of the realigned EPI images (using mean of the realigned EPI images), after which the anatomical image was normalized in space using the MNI (Montreal Neurological Institute, Canada) T1 brain template included in the SPM2. Transformation parameters calculated at that step were applied to spatially normalize all the EPI images that were also resliced at that step to a voxel size of 3 × 3 × 3 mm and then smoothed by an isotropic Gaussian kernel of 10 mm.

The statistical analysis was done in two steps. At the first step, the fixed-effects statistical analysis was performed for each subject using a group box-car model with 6 realignment parameters included as covariates of no interest to ensure that no head-motion-related signal changes would be observed. Design matrix of the linear model was convolved with a canonical hemodynamic response function. Data were high-pass filtered (128 s cutoff period) to minimize low-frequency signal fluctuations. Between- and within-language differences in brain activation in the INFL and MM conditions were obtained for each participant by linear contrasts. The between-language contrasts were obtained by first subtracting the REST condition from either INFL or MM condition of a corresponding language-specific session, and then comparing the results, e.g., “(INFL[fin] minus REST[fin]) vs. (INFL[swe] minus REST[swe])”, where [fin] and [swe] denote the Finnish and Swedish sessions, respectively. The resulting contrast images were used in the second-level statistical analysis treating subjects as random effects in order to make inferences at a population level. In order to follow the analysis approach of the previous study by Lehtonen, Vorobyev, et al. (2006), the second-level analysis was performed with a non-parametric method based on permutations (Statistical non-parametric mapping, SnPM3 version; see Nichols & Holmes, 2002).

In addition to the whole-brain analysis, we also tested the following three spatially constrained hypotheses (see the Introduction) considering possible language-specific activation differences between the INFL and MM conditions inside of the following volumes of interest (VOIs), used previously in Lehtonen, Vorobyev, et al. (2006): the Left Occipito-Temporal Cortex (LOTc, including BA 37 and 19), the Left Posterior Temporal Area (LPTA, including BA 21 and 22), and the Left Inferior Frontal Gyrus (LIFG, including BA 44, 45 and 47). The VOIs were not defined on purely anatomical but also on functional basis and could include bordering areas, e.g., the LIFG included quite a large part of BA 13 belonging to insular cortex adjacent to Broca's area. A binary mask for the LOTc VOI was created as a 15 mm radius sphere centered at the coordinates −44, −58, −15 (x, y, z) as suggested by Jobard et al. (2003) for the mean location of the so-called visual word form area. Binary masks for the latter two VOIs were created with the MRIcro v.1.39 software (Rorden & Brett, 2000) from the corresponding VOI-images (<http://hendrix.imm.dtu.dk/services/jerne/ninf/voi.html>) generated by Nielsen and Hansen (2002) using the BrainMap database (Fox & Lancaster, 1994). The individual contrast images created at the fixed-effect level were multiplied with the VOI masks resulting in 3 sets of masked images with volumes of 11.9 cm³, 18.6 cm³ and 61.2 cm³, for the LOTc, LPTA, and LIFG VOIs, respectively. Each set of the masked images (1 image per subject) was entered into a separate random effects non-parametric model (pseudo *t*-test).

The whole-brain and VOI-based results obtained in the key comparisons between the active tasks were inclusively masked with the corresponding “active task vs. REST state” contrast in order to make sure that the effects obtained in the key comparisons reflect true activations. Voxel threshold for the masks was chosen at the $p < 0.05$ uncorrected level. For example, the result of the above mentioned contrast “(INFL[fin] minus REST[fin]) vs. (INFL[swe] minus R[swe])” was masked with the “(INFL[fin] minus REST[fin])” contrast.

Furthermore, in order to account for possible influences on imaging results by differences in the stimulus duration on the screen due to variable response times, the difference in mean reaction time between the MM and INFL conditions in each language (one mean value per language per subject) was used in an additional series of the second-level SnPM analyses as a confounding covariate. This was done both for the whole brain and for each VOI.

All second-level SnPM analyses were based on 1024 permutations and locally pooled variance estimate with 10 mm smoothing. In the whole-brain SnPM analyses, activations were considered significant if they survived the corrected $p < 0.05$ threshold for the combined (equally weighted; $\theta = 0.5$) cluster volume and peak value w -statistics (the so-called meta-combined or combo test, see Hayasaka & Nichols, 2004). In the VOI SnPM analyses, the results were thresholded at $p < 0.05$ voxel level, corrected for the family-wise error (FWE) rate in a given volume of interest. Activation peaks were described according to the Talairach and Tournoux (1988) coordinate system.

3. Results

3.1. Behavioral results

None of the participants exceeded the preset error rate criterion of 15% in either of the language parts of the experiment. The error rates of the participants varied between 0.29% and 9.41% (mean, 2.68; SD, 2.1) in the Finnish part and between 0.29% and 5.76% (mean, 1.87; SD, 1.5) in the Swedish part. Prior to data analyses, incorrect responses and response latencies longer than three standard deviations above individual mean value were discarded from the data. A two-way repeated measures analysis of variance (ANOVA) (language \times morphological structure) was performed for RTs and error rates of words and pseudowords separately.⁴

The RT results for words (see Fig. 1) showed a significant main effect of language ($F(1,15) = 19.1$, $p = 0.001$), suggesting that the Finnish words received longer RTs overall than the Swedish words. A significant main effect was also observed for morphological structure ($F(1,15) = 83.0$, $p < 0.001$), stemming from the large RT difference (87 ms) between the inflected and monomorphemic words in the Finnish language. As expected, language and morphological structure interacted ($F(1,15) = 54.5$, $p < 0.001$), reflecting the fact that the Finnish inflected words were recognized more slowly (708 ms) than the monomorphemic words (621 ms), while in Swedish the RTs to these word types did not differ (inflected, 620 ms; monomorphemic, 620 ms). This pattern was confirmed in paired t -tests investigating the differences directly: in Finnish, the inflected words differed significantly from the monomorphemic words ($t(15) = 9.05$, $p < 0.001$), but this was not the case in Swedish where they showed similar RTs ($t(15) = 0.15$, $p = 0.886$). The RTs to the monomorphemic words did not differ between languages ($t(15) = 0.96$, $p = 0.925$), reflecting the careful matching of the stimuli. With regard to the error rate patterns of the real words, no significant effects were shown in the ANOVA (main effect for language, $F(1,15) < 1$; main effect for morphology, $F(1,15) = 2.76$, $p = 0.117$; interaction between language and morphology, $F(1,15) < 1$).

For the pseudowords, the ANOVA for RTs showed significant main effects for morphology ($F(1,15) = 10.1$, $p = 0.006$) and for language ($F(1,15) = 8.44$, $p = 0.011$) as well as a significant interaction between the two factors ($F(1,15) = 7.24$, $p = 0.017$), reflecting the fact that the inflected pseudowords

⁴ For one participant, behavioral data from the first session of the Swedish part (70 items including all item types) is not included in the reported behavioral analyses due to a technical problem in registering button presses during the beginning of the fMRI scanning. Yet, these items were re-run after the end of the Swedish part, and analyses showed that inclusion of this data would not have changed the overall pattern of behavioral results.

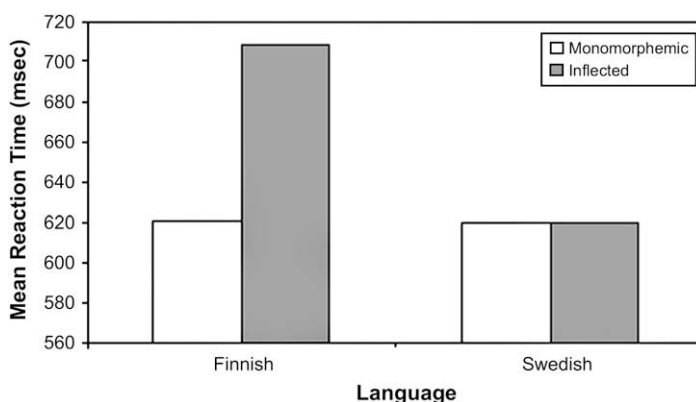


Fig. 1. Reaction time patterns for the inflected vs. monomorphemic words in Finnish and Swedish.

elicited significantly longer RTs than the monomorphemic pseudowords in Finnish (inflected, 867 ms; monomorphemic, 835 ms) but not in Swedish (inflected, 758 ms; monomorphemic, 759 ms). This finding was confirmed in paired *t*-tests between the inflected and the monomorphemic pseudowords in each language (for Finnish, $t(15) = 4.08$, $p = 0.001$; for Swedish, $t(15) = 0.14$, $p = 0.888$). For error rates, no significant effects were observed in a repeated measures ANOVA (main effect for morphology, $F(1,15) < 1$; main effect for language, $F(1,15) = 2.78$, $p = 0.116$; interaction between language and morphology, $F(1,15) < 1$). Thus a morphological processing cost for the pseudowords was observed in RTs in Finnish but not in Swedish, which is likely to reflect strategic factors elicited by the real word stimuli of each language and their processing requirements.

3.2. fMRI results

3.2.1. Whole-brain analysis

The random-effects analysis for the whole brain (Table 2, Fig. 2) revealed that the lexical decision task with inflected Finnish words activated the left inferior BA 44 more strongly than did the same task with either Swedish inflected or with Finnish non-inflected words. Moreover, there was a large area of

Table 2

Location and statistical values of the peaks obtained in the whole-brain SnPM random effects analysis for the two contrasts involving processing inflected words in Finnish.

Contrasts:	INFL [fin] vs. INFL [swe]				INFL [fin] vs. MM [fin]			
	w (p-Value)	x	y	z	w (p-Value)	x	y	z
Brain Structure								
Left inferior frontal gyrus, BA 44	4.41 (0.044)	−54	12	27	4.29 (0.048)	−51	9	24
Left precentral sulcus, BA 6/44		−57	9	15				
		−48	0	36				
Left inferior occipital gyrus, BA 18	4.27 (0.049)	−33	−90	−12				
Left fusiform gyrus, BA 19 ^a		−36	−75	−21				

p = corrected for volume chance probability for the combo *w* statistics.

^a In order to account for a discrepancy between the MNI and Talairach coordinate spaces (Brett, Johnsrude, & Owen, 2002) that is particularly noticeable in the inferior parts of the brain, a non-linear coordinate transformation utility “mni2tal” by M. Brett (<http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach>) was used to localize this activation peak. After the transformation, the peak falls into fusiform gyrus, though we cannot exclude that the activation might spread also to cerebellar cortex (see e.g., Fig. 2).

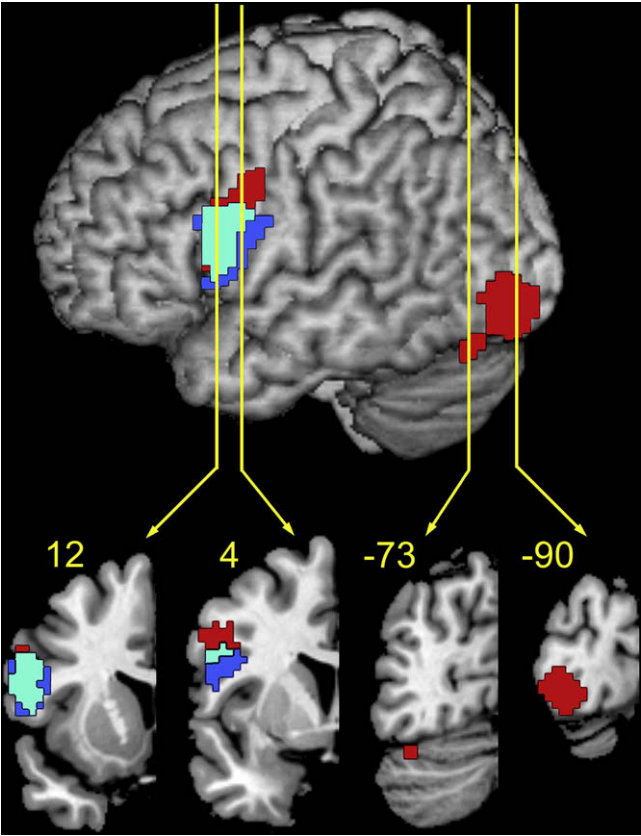


Fig. 2. Areas where activation was stronger ($p < 0.05$ corrected, combo w-test, SnPM) for Finnish inflected words than for either Swedish inflected words (red), or Finnish monomorphemic words (blue). The overlapping area between the two contrasts is shown in cyan. The areas are shown as projections onto the reconstructed left hemisphere surface of the MNI brain template, and in a series of coronal sections through the left hemisphere, made at 4 arbitrary planes indicated by the position of yellow lines over the reconstructed brain surface. Numbers denote the y (anterior to posterior) coordinate of the section planes in the MNI space.

Table 3
Location and statistical values of the peaks obtained in the VOI SnPM random effects analysis of the inflected vs. monomorphemic contrast of the Finnish part.

VOI	No confound		RT difference as confound		MNI coordinates		
	<i>t</i> (<i>p</i> -Value)	<i>k</i>	<i>t</i> (<i>p</i> -Value)	<i>k</i>	<i>x</i>	<i>y</i>	<i>z</i>
Brain structure							
LOTCT VOI							
Posterior inferior temporal sulcus, BA 37	4.45 (0.003)	5	4.34 (0.002)	5	−48	−48	−3
LPTA VOI							
Posterior middle temporal gyrus, BA 21	3.91 (0.010)	27	3.81 (0.012)	25	−48	−48	3
LIFG VOI							
Inferior frontal gyrus, BA 44	4.50 (0.010)	49	4.41 (0.012)	28	−51	9	24

t = pseudo *t*-values (*p*, Family-wise error (FWE) corrected), *k* = cluster size in voxels.

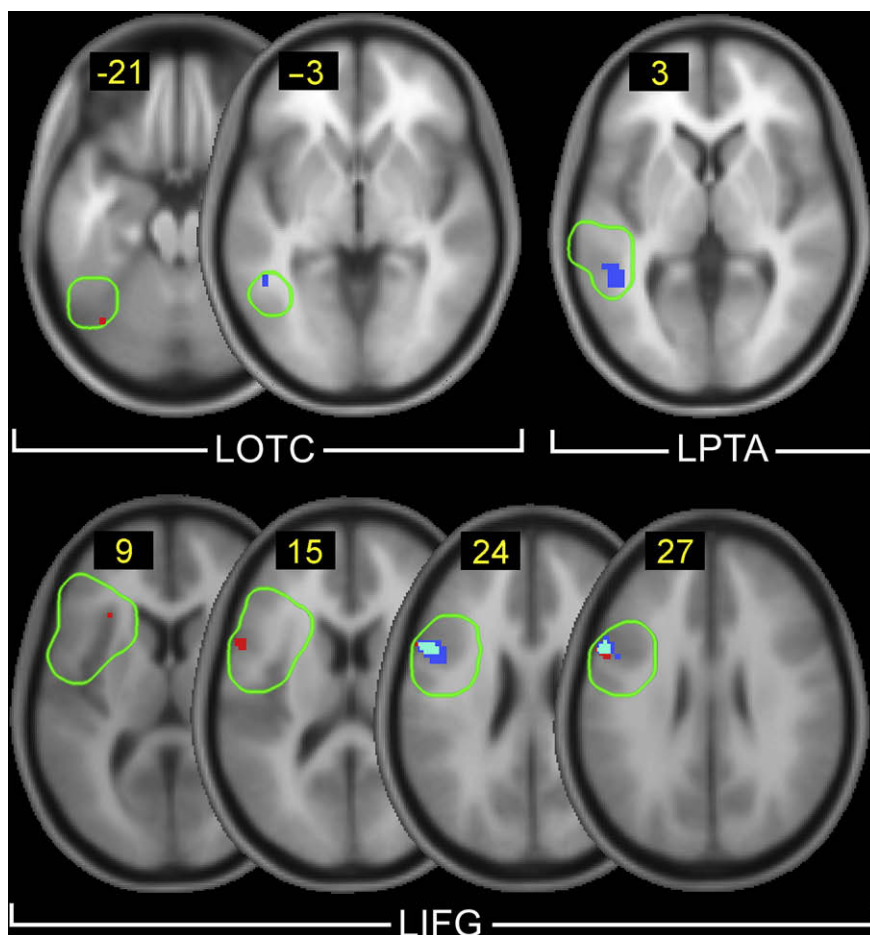


Fig. 3. Location of the significantly ($p < 0.05$ FWE corrected, pseudo t -test, SnPM) activated voxels for Finnish inflected words vs. for either Swedish inflected words (red), or Finnish monomorphemic words (blue). The overlapping area between the two contrasts is shown in cyan. The activations and contours of the VOIs (green) are shown on the series of axial MNI brain template planes crossing the activation peaks (see Tables 3 and 4) obtained in the LOTC (top row, left), LPTA (top row, right), and LIFG (bottom row) VOIs. Numbers denote the z-coordinate in the MNI space.

overlap between the results of the two contrasts. In addition, the left extrastriate cortex showed stronger activation for Finnish inflected words than for Swedish inflected words. No significant results were obtained in between-language contrasts when both languages were represented by monomorphemic words. Similarly, no significant activations were found between Swedish inflected vs. monomorphemic words. The inclusion of the RT difference as a covariate did not alter the whole-brain analysis results.

3.2.2. VOI analyses

For Finnish, the SnPM analysis revealed a statistically significant activation in the INFL vs. MM contrast in all the tested VOIs both when the RT difference was included as a confounding covariate in the model and when it was absent (see Table 3 and Fig. 3). The activation peaks were located in BA 37 for the LOTC, in BA 21 for the LPTA and BA 44 for the LIFG VOI (Fig. 3). The peak in the LOTC VOI was, however, situated so superiorly and so close to the peaks in the very posteriorly located peak of the LPTA VOI that it is likely to belong to the same cluster as the LPTA peak. For Swedish, no differences

Table 4
Location and statistical values of the peaks obtained in the VOI SnPM random effects analysis of the inflected words in the contrast between Finnish and Swedish.

VOI	No confound		RT difference as confound		MNI coordinates		
	<i>t</i> (<i>p</i> -Value)	<i>k</i>	<i>t</i> (<i>p</i> -Value)	<i>k</i>	<i>x</i>	<i>y</i>	<i>z</i>
LOTC VOI							
Left fusiform gyrus, BA 19 ^a	3.27 (0.038)	1	3.26 (0.049)	1	−39	−69	−21
LIFG VOI							
Inferior frontal gyrus, BA 44	4.34 (0.010)	32	4.26 (0.022)	26	−54	12	27
Anterior insula, BA 13	3.88 (0.036)	1	3.81 (0.047)	1	−30	24	9
Anterior insula, BA 13	3.84 (0.040)	1	3.77 (0.049)	1	−33	21	6
Inferior frontal gyrus/anterior insula, BA 47/13	3.79 (0.044)	1	–	–	−33	24	−3

t = pseudo *t*-values (*p*, Family-wise error (FWE) corrected), *k* = cluster size in voxels.
^a In order to account for a discrepancy between the MNI and Talairach coordinate spaces (Brett et al., 2002) that is particularly noticeable in the inferior parts of the brain, a non-linear coordinate transformation utility “mni2tal” by M. Brett (<http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach>) was used to localize this activation peak. After the transformation, the peak falls into the fusiform gyrus, though we cannot exclude that the activation might spread also to the cerebellar cortex (see Fig. 3).

were observed between the inflected and monomorphemic conditions (with the exception of the LPTA VOI where a single voxel was activated for the monomorphemic vs. inflected contrast when the RT confound was not included in the model). Direct contrasts between the inflected words of Finnish vs. Swedish revealed increased activation in the LIFG VOI (BAs 44, 13, and 47/13) and in the LOTC VOI (BA 19) when no confounding covariate was used (see Table 4 and Fig. 3). These results were confirmed in analyses where the RT difference was used as a covariate, except for the peak in BA 47/13 (Table 4). In the LPTA VOI, there were no significant activation increases in the contrasts between inflected Finnish vs. Swedish words. The contrast between the monomorphemic words of the two languages did not elicit any activation increases. Similarly, the opposite contrasts (Swedish vs. Finnish) did not reveal any significant effects.

4. Discussion

The present study investigated morphological processing in two structurally different languages within the same individuals. We tested the assumption that the distinct behavioral effects related to the recognition of inflected words in Finnish vs. Swedish would be reflected in differential brain activation patterns for early, high-proficient bilinguals, reflecting a structural aspect upon which the two languages clearly differ from each other. While most previous studies have studied the two morphological processing routes (storage and decomposition) within the same language and often with the regular vs. irregular distinction, we employed a cross-language setting with a direct contrast between morphologically complex vs. simple words. As predicted, the recognition of inflected vs. monomorphemic words in the morphologically rich Finnish indeed elicited increases in brain activation that were not observed in the corresponding contrast in the morphologically more limited Swedish. These results suggest a language-specific neural processing difference as a consequence of the major structural difference between these two languages. The behavioral performance of the bilingual participants on the monomorphemic control words was similar in both languages, and the language skills were estimated to be rather balanced and at a high level, suggesting that task difficulty or differential language proficiency is unlikely to be the primary cause of the differences. If anything, the bilinguals may have been slightly Swedish-dominant as a group, but even in their less dominant language they were like monolingual speakers. In other words, they showed a similar pattern of results to that of the Finnish monolinguals in a corresponding previous study (Lehtonen, Vorobyev, et al., 2006), namely increased activation for the inflected vs. monomorphemic Finnish nouns in the LIFG and in the LPTA.

For Finnish, earlier behavioral studies indicate that decomposition is the dominant way of processing inflected words, and this decomposition process was shown to activate areas that were not

activated by inflected Swedish words which, according to this interpretation, are recognized as full forms. Nevertheless, we believe that similar brain areas to those observed here could also be activated in Swedish in a situation where decomposition takes place, namely, for recognition of low frequency inflected words. In other words, it is the balance of storage and decomposition that seems to differ between these two languages studied. Earlier studies conducted in bilinguals generally show that identical brain areas are used to perform identical tasks in two languages (Abutalebi & Green, 2007). It is likely that similar brain areas are also responsible for the core aspects of morphological decomposition across languages. The exact processing requirements, such as the contribution of semantic, syntactic and morpho-phonological factors may naturally further modulate the activation of brain regions related to morphological decomposition.

The findings of the current study concerning Finnish were similar to those observed by Lehtonen, Vorobyev, et al. (2006) in Finnish monolinguals. In the present study, increased activation for Finnish inflected vs. monomorphemic words was found in all of the three VOIs, but the peak of the LOTC was concluded to belong to the same cluster as the peak in the LPTA, making its role in the visual word form processing stage unlikely. Observations by Jobard et al. (2003), and Jobard, Vigneau, Mazoyer, and Tzourio-Mazoyer (2007) indicate that the area in the ventral occipito-temporal cortex involved in language processing can be subdivided into modality-specific and amodal parts. The more posterior region (e.g., with *y*-coordinates of about -72 to -56) is activated more for purely visual than auditory stimuli, while the more anterior region (e.g., with *y*-coordinates of about -60 to -41) is activated as a response to both auditory and visual words and can thus be seen as an amodal or multimodal language area. It is therefore likely that the present peak in the LOTC that was rather anteriorly and superiorly situated (see Table 3) was not reflecting visual word form processing but instead related to lexical-semantic processing. On the other hand, the peak in the LOTC in the cross-language comparison between Finnish vs. Swedish inflected words was situated more posteriorly (see Table 4) and following Jobard et al. (2003, 2007) could thus be related to stronger visual word form processing, possibly to processing of some visual sublexical features (Vinckier et al., 2007), in Finnish inflected words.

The activation in the LIFG for Finnish inflected words was the most robust activation peak as it was activated even in the whole-brain analyses and in both within-language and cross-language contrasts. This region has also previously figured most often in imaging studies on morphological processing (e.g., Laine, Rinne, et al., 1999; Marangolo et al., 2006; Tyler et al., 2005; Vannest et al., 2005; Yokoyama et al., 2006), including the previous visual lexical decision study in Finnish (Lehtonen, Vorobyev, et al., 2006). However, in the contrast between inflected vs. monomorphemic Finnish words, the precise location of the peak in the LIFG was situated more dorsally (in BA 44) in the present participant group than in that previous study (in BA 47). A functional subdivision in the left inferior frontal gyrus has been proposed, suggesting that the more ventral parts (BAs 47/45) are related to semantic processing while the more dorsal parts (BA 44/45) are associated with phonological (Jobard et al., 2003) or syntactic processing (Friederici et al., 2000; Grodzinsky & Friederici, 2006; Newman, Just, Keller, Roth, & Carpenter, 2003). It is possible that the differences are due to the different inflectional endings used: most of the Finnish inflectional endings in the present study were genitive forms, which are in fact more syntactic in nature than the more semantic inessive endings (e.g., *talo + ssa* = 'house' + 'in') used by Lehtonen, Vorobyev, et al. (2006). This feature may have elicited a different activation pattern in the LIFG between the two studies.

With regard to the effects modulated by the chosen suffixes, one could also speculate as to whether the employment of different suffixes in Finnish and Swedish is contributing to the differences observed between the languages. It could be that the characteristics of affixes also modulate the balance of storage and decomposition in a given language. Yet, for singular noun forms, the only common case in Finnish and Swedish is the genitive, but it is most often accompanied with a definite form in Swedish, making the words trimorphemic. Definiteness, on the other hand, is a linguistic feature that does not have a similar marker in Finnish. We cannot exclude the possibility that the cases used affected the effects observed, and further studies, e.g., with other languages that have a wider selection of corresponding inflectional forms could be conducted to resolve this issue.

Both Lehtonen, Vorobyev, et al. (2006) and the present study found increased activation for inflected words in the LIFG and in the LPTA, but no robust effects in the LOTC. It can thus be concluded

that these early Finnish–Swedish bilinguals processed Finnish inflected words in a similar way to Finnish monolinguals. In addition, the present study provides further evidence that the morphological processing cost stems from the later semantic-syntactic stage where the morpheme-based lexical and semantic representations are accessed and integrated, rather than from the early visual word form stage where the stems are segmented from the suffixes. This finding is also in line with the previous behavioral study by Hyönä et al. (2002) as well as the ERP study of Lehtonen et al. (2007) which showed no early effects for Finnish inflected vs. monomorphemic words but effects at later time-windows, in the N400 and P600-like components.

The lack of an effect in the LOTC in the within-language contrast in Finnish does not necessarily indicate that early decomposition would not take place with these inflected words. As noted earlier, it is possible that the early access to the decomposed morpheme representations is too automatic to be caught with the present task and methodology. Moreover, the cross-language effect in the left fusiform gyrus for Finnish vs. Swedish inflected words suggests increased demands for decomposable words at the visual word form level. The involvement of the left occipito-temporal region in morphological processing has previously been reported in studies employing visual masked priming (Devlin et al., 2004; Gold & Rastle, 2007) where very short prime presentation times are used and which may therefore put more emphasis on the early processing stage than the present task.

The LIFG and the LPTA where significant activation increases for Finnish inflected words were observed are regions that have been found to be an integral part of the network involved in semantic and syntactic processing during language comprehension (Démonet et al., 2005; Grodzinsky & Friederici, 2006; Jobard et al., 2003; Vigneau et al., 2006), and we attribute these activations to the later level of morphological decomposition where the meaning and syntactic aspects of the constituents are accessed and integrated. More specifically, Lehtonen, Vorobyev, et al. (2006) proposed that the activation of the posterior temporal areas could be related to accessing the semantic and syntactic representations of stems and suffixes, while the inferior frontal regions were involved in the more active on-line integration of the constituents (cf. Hagoort, 2005). This integration may involve active retrieval of the meaning of the constituents and construction of a semantic-syntactic interpretation of the particular stem + suffix combination in working memory, perhaps together with the activation of the posterior temporal areas and possibly of other frontal regions as well. Tyler et al. (2005) who found activation both for regularly inflected (e.g., *stayed*) and so-called pseudoregulars (monomorphemic words which had a suffix-like ending phonologically, e.g., *trade*) in these two areas proposed that the frontal activation would reflect automatic morpho-phonological segmentation of suffixes from the auditorily presented words and the temporal areas would be related to accessing the stems of those words. In studies using masked priming (Devlin et al., 2004; Gold & Rastle, 2007), the left middle temporal gyrus where the present LPTA peak was observed has been sensitive to lexical-semantic priming, indicating access to such representations. More generally, in comprehension tasks the middle temporal gyrus has been associated with lexical and semantic access in both visual and auditory modalities (Jobard et al., 2003) but also with integration of complex linguistic elements, especially with sentences and texts (Vigneau et al., 2006). The posterior temporal regions may thus also have an integrative function (see also Grodzinsky & Friederici, 2006). It is, however, not possible to distinguish between these alternatives on the basis of the present study, and further studies are clearly required for specifying the exact computational operations performed in each of the areas that are active during morphological decomposition.

Employing the blocked design entails that the pseudowords were also included in the analyses. We made this choice in the experimental setup in order to follow the design used in the corresponding study in Finnish monolinguals. The other reason was to gain stronger statistical power: we expected the morphological effects on brain activation to be rather weak both on the basis of previous related imaging studies and because the critical contrast (bimorphemic vs. monomorphemic words) comprised of a rather small difference between the stimuli. With the current setup, we cannot exclude the possibility that the pseudowords may also have contributed to the observed brain activation results. Yet, the activation difference between “inflected” pseudowords and “monomorphemic” pseudowords (and the lack of it in the Swedish case) should stem from the same morphological process as the difference between inflected vs. monomorphemic real words. This is supported by the fact that the behavioral results showed a significant morphological processing cost also for the pseudowords in

Finnish but not in Swedish, similarly to the real words. It should also be noted that there are two studies that have been conducted investigating brain responses with inflected Finnish words in an event-related design, and they show effects that are in line with the present results. The ERP study of Lehtonen et al. (2007) used visual lexical decision and showed neural effects for inflected vs. monomorphemic words at later, semantic-syntactic time-windows and components even with fully randomized stimulus presentation. Similar effects were also observed in a very recent MEG study employing silent reading of real Finnish words (no pseudowords were included in the stimuli): morphological effects in the same contrast were observed from about 200 ms onwards in left superior temporal areas (Vartiainen, Aggijaro, Lehtonen, Hultén, Laine, & Salmelin, in press).

5. Conclusion

The present study showed neural evidence for different morphological processing patterns in two structurally different languages within the same individuals. Differences were seen in the recognition of inflected nouns, where both a behavioral and neural processing cost was observed in the morphologically rich Finnish, while no effects of morphological complexity were found in the morphologically more limited Swedish. This finding suggests decomposition in Finnish and full-form recognition in Swedish. The recognition of inflected vs. monomorphemic Finnish words showed increased activation mainly in areas related to lexical-semantic and syntactic processing. This finding is in line with previous studies in Finnish monolinguals and suggests that the morphological processing cost primarily stems from the later semantic-syntactic integration stage, instead of the early visual word form stage.

Acknowledgements

This study was financially supported by a grant (#20010) from the Joint Committee of the Nordic Social Science Research Councils (NOS-S) for the last author, and by the Finnish National Graduate School of Psychology, the Ella and Georg Ehrnrooth Foundation, the Foundation for Swedish Culture in Finland, and the Emil Aaltonen Foundation for the first author.

References

- Abutalebi, J., & Green, D. (2007). Bilingual language production: the neurocognition of language representation and control. *Journal of Neurolinguistics*, 20, 242–275.
- Ahlsén, E. (1994). Cognitive morphology in Swedish: studies with normals and aphasics. *Nordic Journal of Linguistics*, 17, 61–73.
- Alegre, M., & Gordon, P. (1999). Frequency effects and the representational status of regular inflections. *Journal of Memory and Language*, 40, 41–61.
- Baayen, R. H., Dijkstra, T., & Schreuder, R. (1997). Singulars and plurals in Dutch: evidence for a parallel dual route model. *Journal of Memory and Language*, 37, 94–117.
- Beretta, A., Campbell, C., Carr, T. H., Huang, J., Schmitt, L. M., Christianson, K., et al. (2003). An ER-fMRI investigation of morphological inflection in German reveals that the brain makes a distinction between regular and irregular words. *Brain and Language*, 85, 67–92.
- Bick, A., Goelman, G., & Frost, R. (2008). Neural correlates of morphological processing in Hebrew. *Journal of Cognitive Neuroscience*, 20, 406–420.
- Brett, M., Johnsrude, I. S., & Owen, A. M. (2002). The problem of functional localization in the human brain. *Nature Reviews Neuroscience*, 3, 243–249.
- Butterworth, B. (1983). Lexical representation. In B. Butterworth (Ed.), *Language production*, Vol. 2 (pp. 257–294). London: Academic Press.
- 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.
- Dehaene, S., Le Clec'h, G., Poline, J. B., Le Bihan, D., & Cohen, L. (2002). The visual word form area: a prelexical representation of visual words in the fusiform gyrus. *NeuroReport*, 13, 321–325.
- Démonet, J.-F., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: functional neuroimaging. *Physiological Reviews*, 85, 49–95.
- Desai, R., Conant, L. L., Waldron, E., & Binder, J. R. (2006). fMRI of past tense processing: the effects of phonological complexity and task difficulty. *Journal of Cognitive Neuroscience*, 18, 278–297.
- 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 of the United States of America*, 101, 14984–14988.
- Fiez, J. A., & Petersen, S. E. (1998). Neuroimaging studies of word reading. *Proceedings of the National Academy of Sciences of the United States of America*, 95, 914–921.

- Fox, P. T., & Lancaster, J. L. (1994). Neuroscience on the net. *Science*, 266, 994–996.
- Frackowiak, R. S. J., Friston, K. J., Firth, C. D., Dolan, R. J., Price, C. J., Zeki, S., et al. (2004). *Human brain function* (2nd ed.). San Diego: Academic Press.
- Friederici, A. D., Opitz, B., & von Cramon, Y. (2000). Segregating semantic and syntactic aspects of processing in the human brain: an fMRI investigation of different word types. *Cerebral Cortex*, 10, 698–705.
- Giraudo, H., & Grainger, J. (2000). Effects of prime word frequency and cumulative root frequency in masked morphological priming. *Language and Cognitive Processes*, 15, 421–444.
- Giraudo, H., & Grainger, J. (2001). Priming complex words: evidence for supralexical representation of morphology. *Psychonomic Bulletin & Review*, 8, 127–131.
- Gold, B. T., & Rastle, K. (2007). Neural correlates of morphological decomposition during visual word recognition. *Journal of Cognitive Neuroscience*, 19, 1983–1993.
- Grodzinsky, Y., & Friederici, A. (2006). Neuroimaging of syntax and syntactic processing. *Current Opinion in Neurobiology*, 16, 240–246.
- Hagoort, P. (2005). On Broca, brain and binding: a new framework. *Trends in Cognitive Sciences*, 9, 416–423.
- Hay, J. (2001). Lexical frequency in morphology: is everything relative? *Linguistics*, 39, 1041–1070.
- Hayasaka, S., & Nichols, T. E. (2004). Combining voxel intensity and cluster extent with permutation test framework. *NeuroImage*, 23, 54–63.
- Hyönä, J., Laine, M., & Niemi, J. (1995). Effects of word's morphological complexity on readers' eye fixation patterns. In J. M. Findlay, R. Kentridge, & R. Walker (Eds.), *Eye movement research: Mechanisms, processes and applications* (pp. 445–452). Amsterdam: Elsevier.
- Hyönä, J., Vainio, S., & Laine, M. (2002). A morphological effect obtains for isolated words but not for words in sentence context. *European Journal of Cognitive Psychology*, 14, 417–433.
- Jaeger, J. J., Lockwood, A. H., Kemmerer, D. L., Van Valin, R. D., Jr., Murphy, B. W., & Khalak, H. G. (1996). A positron emission tomographic study of regular and irregular verb morphology in English. *Language*, 72, 451–497.
- Joanisse, M. F., & Seidenberg, M. S. (2005). Imaging the past: neural activation in frontal and temporal regions during regular and irregular past-tense processing. *Cognitive, Affective & Behavioral Neuroscience*, 5, 282–296.
- Jobard, G., Crivello, F., & Tzourio-Mazoyer, N. (2003). Evaluation of the dual-route theory of reading: a meta-analysis of 35 neuroimaging results. *NeuroImage*, 20, 693–712.
- Jobard, G., Vigneau, M., Mazoyer, B., & Tzourio-Mazoyer, N. (2007). Impact of modality and linguistic complexity during reading and listening tasks. *NeuroImage*, 34, 784–800.
- Laine, M., & Koivisto, M. (1998). Lexical access to inflected words as measured by lateralized visual lexical decision. *Psychological Research*, 61, 220–229.
- Laine, M., Niemi, J., Koivuselkä-Sallinen, P., Ahlsén, E., & Hyönä, J. (1994). A neurolinguistic analysis of morphological deficits in a Finnish–Swedish bilingual aphasic. *Clinical Linguistics and Phonetics*, 8, 177–200.
- Laine, M., Niemi, J., Koivuselkä-Sallinen, P., & Hyönä, J. (1995). Morphological processing of polymorphemic nouns in a highly inflecting language. *Cognitive Neuropsychology*, 12, 457–502.
- Laine, M., Rinne, J. O., Krause, B. J., Teräs, M., & Sipilä, H. (1999). Left hemisphere activation during processing of morphologically complex word forms in adults. *Neuroscience Letters*, 271, 85–88.
- Laine, M., Vainio, S., & Hyönä, J. (1999). Lexical access routes to nouns in a morphologically rich language. *Journal of Memory and Language*, 40, 109–135.
- Laine, M., & Virtanen, P. (1999). *WordMill lexical search program*. Centre for Cognitive Neuroscience, University of Turku.
- Lehtonen, M., Cunillera, T., Rodríguez-Fornells, A., Hultén, A., Tuomainen, J., & Laine, M. (2007). Recognition of morphologically complex words in Finnish: evidence from event-related potentials. *Brain Research*, 1148, 123–137.
- Lehtonen, M., & Laine, M. (2003). How word frequency affects morphological processing in monolinguals and bilinguals. *Bilingualism: Language and Cognition*, 6, 213–225.
- Lehtonen, M., Niska, H., Wande, E., Niemi, J., & Laine, M. (2006). Recognition of inflected words in a morphologically limited language: frequency effects in monolinguals and bilinguals. *Journal of Psycholinguistic Research*, 35, 121–146.
- Lehtonen, M., Vorobyev, V. A., Hugdahl, K., Tuokkola, T., & Laine, M. (2006). Neural correlates of morphological decomposition in a morphologically rich language: an fMRI study. *Brain and Language*, 98, 182–193.
- Leinonen, A., Grönholm-Nyman, P., Järvenpää, M., Söderholm, C., Lappi, O., Laine, M., et al. (2009). Neurocognitive processing of auditorily and visually presented inflected words and pseudowords: evidence from a morphologically rich language. *Brain Research*, 1275, 54–66.
- McCandliss, B., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences*, 7, 293–299.
- Marangolo, P., Piras, F., Galati, G., & Burani, C. (2006). Functional anatomy of derivational morphology. *Cortex*, 42, 1093–1106.
- Newman, S. D., Just, M. A., Keller, T. A., Roth, J., & Carpenter, P. A. (2003). Differential effects of syntactic and semantic processing on the subregions of Broca's area. *Cognitive Brain Research*, 16, 297–307.
- Nichols, T. E., & Holmes, A. P. (2002). Nonparametric permutation tests for functional neuroimaging: a primer with examples. *Human Brain Mapping*, 15, 1–25.
- Nielsen, F. Å., & Hansen, L. K. (2002). Automatic anatomical labeling of Talairach coordinates and generation of volumes of interest via the BrainMap database. *NeuroImage*, 165, 490.
- Niemi, J., Laine, M., & Tuominen, J. (1994). Cognitive morphology in Finnish: foundations of a new model. *Language and Cognitive Processes*, 3, 423–446.
- Palti, D., Ben Shachar, M., Hendler, T., & Hadar, U. (2007). Neural correlates of semantic and morphological processing of Hebrew nouns and verbs. *Human Brain Mapping*, 28, 303–314.
- Rorden, C., & Brett, M. (2000). Stereotaxic display of brain lesions. *Behavioural Neurology*, 12, 191–200.
- Sach, M., Seitz, R. J., & Indefrey, P. (2004). Unified inflectional processing of regular and irregular verbs: a PET study. *NeuroReport*, 15, 533–537.
- Sahin, N. T., Pinker, S., & Halgren, E. (2006). Abstract grammatical processing of nouns and verbs in Broca's area: Evidence from fMRI. *Cortex*, 42, 540–562.

- Schreuder, R., & Baayen, R. H. (1995). Modelling morphological processing. In L. B. Feldman (Ed.), *Morphological aspects of language processing* (pp. 131–154). Hillsdale, New Jersey: Lawrence Erlbaum.
- Sereno, J. A., & Jongman, A. (1997). Processing of English inflectional morphology. *Memory & Cognition*, 25, 425–437.
- Stockall, L., & Marantz, A. (2006). A single route, full decomposition model of morphological complexity. MEG evidence. *The Mental Lexicon*, 1, 85–123.
- Taft, M. (1979). Recognition of affixed words and the word frequency effect. *Memory & Cognition*, 7, 263–272.
- Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain. 3-D proportional system: An approach to cerebral imaging*. Stuttgart/New York: Georg Thieme Verlag.
- Tyler, L. K., Stamatakis, E. A., Post, B., Randall, B., & Marslen-Wilson, W. (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, Behavioral and Affective Neuroscience*, 5, 67–76.
- Vartiainen, J., Aggujaro, S., Lehtonen, M., Hultén, A., Laine, M., Salmelin, R. (in press). Neural dynamics of reading morphologically complex words. *NeuroImage*.
- Vigneau, M., Beaucousin, V., Hervé, P. Y., Duffau, H., Crivello, F., Houdé, O., et al. (2006). Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. *NeuroImage*, 30, 1414–1432.
- Vinckier, F., Dehaene, S., Jobert, A., Dubus, J. P., Sigman, M., & Cohen, L. (2007). Hierarchical coding of letter strings in the ventral stream: dissecting the inner organization of the visual word-form system. *Neuron*, 55, 143–156.
- Yokoyama, S., Miyamoto, T., Riera, J., Kim, J., Akitsuki, Y., Iwata, K., et al. (2006). Cortical mechanisms involved in the processing of verbs: an fMRI study. *Journal of Cognitive Neuroscience*, 18, 1304–1313.