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Morphological processing in the brain: The good (inflection), the bad (derivation) and the ugly (compounding)

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ABSTRACT

There is considerable behavioral evidence that morphologically complex words such as ‘tax-able’ and ‘kiss-es’ are processed and represented combinatorially. In other words, they are decomposed into their constituents ‘tax’ and ‘-able’ during comprehension (reading or listening), and producing them might also involve on–the–spot combination of these constituents (especially for inflections). However, despite increasing amount of neurocognitive research, the neural mechanisms underlying these processes are still not fully understood. The purpose of this critical review is to offer a comprehensive overview on the state-of-the-art of the research on the neural mechanisms of morphological processing. In order to take into account all types of complex words, we include findings on inflected, derived, and compound words presented both visually and aurally. More specifically, we cover a wide range of electro- and magnetoencephalography (EEG and MEG, respectively) as well as structural/functional magnetic resonance imaging (s/fMRI) studies that focus on morphological processing. We present the findings with respect to the temporal course and localization of morphologically complex word processing. We summarize the observed findings, their interpretations with respect to current psycholinguistic models, and discuss methodological approaches as well as their possible limitations.

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1. Introduction

A significant portion of the psycholinguistic literature in the past several decades has been concerned with the processing of morphologically complex words. Despite an increasing number of studies on the neural underpinnings of morphological processing, its time-course and the underlying brain networks are still far from being clearly identified. In this paper, we present a much needed comprehensive review of the studies which have used some of the main neuroimaging methods, in order to grasp the state-of-the-art in the cognitive neuroscience of morphological processing. Thus, the main aim of this methodological review is to provide cognitive (neuro-) scientists interested in conducting neuroimaging research on morphological processing with a comprehensive summary of the most relevant neuroimaging research on this matter. This review mainly focuses and pivots on the experimental methods, and especially on three neuroimaging techniques that are of great relevance for the field, summarizing evidence from studies using Electroencephalography (EEG), Magnetoencephalography (MEG) and structural and functional Magnetic Resonance Imaging (MRI). The review is organized in three main sections corresponding to the three main morphological operations: inflection, derivation, and compounding. In each of the sections, the evidence provided by neuroimaging studies using the three main techniques mentioned above is discussed. We selected only studies that were conducted with a) adult, b) healthy, c) native speakers of the test language d) without reading difficulties. In most cases, the participants of the reviewed studies are students at universities (whose reading skills are usually not assessed). We thus have not included studies on language acquisition or on special populations, even if they report a comparison to a control group (i.e. healthy, adult, native speakers with unimpaired reading skills), with the exception of a handful of studies that (a) report native and nonnative speakers together in the absence of between group differences, (b) tested simultaneous bilinguals (2 L1s) in both their languages and (c) link brain structure to morphological processing, which we consider relevant and timely. To this end, the review of functional MRI studies includes 22 studies on inflections, 18 on derivations (note that studies that looked at both inflection and derivation are counted twice) and three on compounding, plus three structural MRI studies; the review of MEG studies includes 7 studies on inflections, 10 on derivations, and two on compounding, and the review of EEG studies provides a selection of 28 papers on inflections, 19 on derivations, and 13 on compounding. This means that the review for MRI and MEG studies is exhaustive at the time of writing of this paper. Because the number of EEG studies on morphological processing is close to hundred, the present review for EEG studies has to be selective, but care was taken that the most relevant and known studies have been included. In addition, we attempt to review and combine those studies that link a specific morphological function (e.g. decomposition/parsing of morphologically complex words) to neural effects (e.g. LAN, P600, N400m effects etc.).

While the main aim of the current methodological review is not to present the readership with an all-inclusive and detailed theoretical discussion of the morphological operations or processes at stake, we believe that a short description and overview of the (psycho-)linguistic models that have been proposed to describe each morphological operation could be beneficial to correctly frame the studies discussed below. For this reason, we start each of the three main sections of this review by briefly summarizing our current theoretical knowledge in the field.

2. Inflectional morphology

Borrowing an illustrative term previously used in the literature (cf. Janda, 2010), inflectional morphemes could be defined as the “glue” of linguistic constructions, systematically materializing in morphemic units the relationships between the different slots that constitute an expression. There are multiple definitions of what inflectional morphology is (see Bybee, 1985), but they all tend to consistently refer to the broad concept of grammar, closely relating inflectional morphemes with syntactic structures. And that is precisely the common denominator of most descriptive approaches to the bound morphemes that constitute the core of inflectional morphology, depicting the rules and principles that govern the relations between the elements of a linguistic expression that ultimately yield the selection of the appropriated closed-class bound morphemic “glue” for each slot.

But if that is indeed the case, and if inflectional morphemes are used to fuse together different parts of speech respecting the grammatical rules and principles of a given language, then it may be worth investigating the cognitive representations of the individual inflectional morphemes that underlie such dynamic blending mechanisms. And this is precisely what the field has been doing for several decades, trying to elucidate when an inflected polymorphemic word is decomposed and its stem accessed, and to what extent this morphological decomposition process depends on the saliency and regularity of the inflectional morphemes (e.g., Caramazza, Laudanna, & Romani, 1988; Stump, 2001).

Most notably, the “English past tense” debate constitutes the hallmark of this issue, given the obvious saliency differences between a regular past tense like *walked* and an irregular one like *ran* (see Marslen-Wilson & Tyler, 1998). Regular inflected forms of the past tense provide a transparent cue to the root, given that the physical form of the stem is usually fully contained in the affixed representation (e.g., *walk* in *walked*). In contrast, irregular forms do not always provide a cue to the stem, since it is not readily available by simple means of grammatical rule implementation (e.g., *run* in *ran*). Do we apply the rules on the fly to create the regular inflected forms or do we store them as independent representations? Do we store the irregular forms as whole-word entries in the mental lexicon? These questions have constituted the grounds for the debate on the English past tense as a landmark issue of the theoretical explanations of inflectional morphology, as will be briefly sketched below.

One way to interpret and account for the processing of inflectional morphology is to assume that the rules that govern the combinatorial morphology are abstract grammatical constructs that are dynamically applied online during word generation by pasting together the base forms and the corresponding inflectional morphemes (e.g., *walk* + *ed*). However, this is a process that cannot be applied to opaque irregular forms, given that their composition is not based on rule-grounded morpheme concatenation (e.g., *run* and *ran*). The solution to this has been to propose the existence of dual-route mechanisms that allow for both a lexical listing route by which stored irregular forms are retrieved, and for a compositional route for regular forms (e.g., Baayen, Dijkstra, & Schreuder, 1997; Marcus et al., 1995; Pinker, 1991). However, this is not the only way to conceive the retrieval and processing of inflected forms, and some other scholars have argued in favor of single-mechanism storage theories by which all possible forms, be they regular or irregular, are fully listed in the lexicon (e.g., Butterworth, 1983) or in contrast, are exclusively the result of the application of combinatorial rules (e.g., Plunkett & Marchman, 1993). A modern version of Chomskyan tradition (e.g., Ullman et al., 1997, 2005), assumes categorical differences between regular and irregular inflections, because the former are processed in the default procedural-memory system in left-frontal structures (including Broca's area and left basal ganglia), while the latter are stored in a lexical declarative-memory system that resides in left temporal/temporo-parietal structures. Another type of dual-mechanism account is the bihemispheric framework developed by Marslen-Wilson and colleagues (Bozic, Tyler, Ives, Randall, & Marslen-Wilson, 2010; Marslen-Wilson & Tyler, 1998, 2007), which argues that a specific left-hemispheric neural system supports processes of regular inflectional morphology, while whole-form and stem-based access processes have a broader bi-hemispheric substrate. Dual-mechanism accounts are contrasted by single system accounts, which assume no principled but rather graded differences between regular and irregular inflection that result from differences in form-to-meaning overlap (e.g., Justus, Larsen, de Mornay Davies, & Swick, 2008; Kielar & Joanisse, 2009) or stem frequency (e.g., Smolka & Eulitz, 2018; Smolka, Khader, Wiese, Zwitserlood, & Rösler, 2013). A full overview of the competing models is beyond the scope of this paper; instead, we will examine the available evidence against the predictions by single- and dual-route approaches.

As we will present below, data from neuroimaging studies seem to support the evidence from other neighboring domains (behavioral, eye-tracking) claiming for different neural substrates and for a different time course of the processing of regular and irregular inflected forms (namely, in support for dual-route models; see Marslen-Wilson & Tyler, 1997; but see Fruchter, Stockall, & Marantz, 2013; Stockall & Marantz, 2006). However, the readership will also see that the distinction between the processing of inflected forms on the basis of their regularity is not always categorical, and that it is sometimes a matter of quantitative differences (e.g., differences in temporal processing, or differences in the lexical and semantic properties of the verbs). Thus, in the following paragraphs we will offer a summarized review of the neuroscientific evidence gathered using EEG, MEG and s/fMRI. As the readership will easily appreciate, most of the studies are based on the past tense debate, and the anglocentric appropriation of this debate has resulted in the mainstream focus being on English, even though many other languages and other inflectional processes have also contributed to our knowledge in recent years. The results of the most studies seem to converge, but the readership will be also able to see some discrepancies that maintain the discussion between single- and dual-route approaches.

2.1. EEG

Inflections are the most well studied morphological class in EEG studies and outnumber those on derivations and compounding. The reason for this can be traced back to the fact that inflections have been the traditional and earliest means to examine theories on word processing, and in particular the theory by Chomsky that differentiates between rule-based and storage-based word processing. Early researchers were intrigued by the idea that the electrophysiology of the brain could settle the issue and thus searched for neural correlates of rules versus storage, and considered inflections as the best means to differentiate between items that go by rule (e.g., *walk-walked*) and those that do not (e.g., *teach-taught*).

Even though there are some studies on plural inflection, most studies have examined verbal inflection and past tense forms, which is the reason why this discussion has been labelled the “past tense debate”. The field has been dominated by studies on English verbal inflection, but includes also insights from Italian, Catalan, Spanish, and German, as well as a few studies in Finnish. The typical paradigms used are the violation paradigm and the (masked or overt) priming paradigm. Table 1 summarizes the here discussed studies and Fig. 1 presents ERP/ERF components related to morphological processing.

2.1.1. *The violation paradigm*

In the violation paradigm, the critical word is typically embedded in a sentence. The violation occurs either with respect to the sentence context (e.g., a present tense verb in a past tense sentence or vice versa, as in *Yesterday I *grind coffee*) or with respect to the inflectional affixes (e.g., a present tense root combined with a past tense suffix, such as **bringed* instead of *brought* or **sept* instead of *seeped*). Violation studies have focused on the EEG correlates that are supposed to represent rule-based/decomposition processes in form of left anterior negativities (LAN; e.g., Krott, Baayen, & Hagoort, 2006), or on EEG correlates that relate to grammatical errors and syntactic reanalysis represented by late positive deflections (P600; e.g., Coulson, King, & Kutas, 1998).

Many different effects surfaced when verb inflections were studied by means of violation paradigms, ranging from no effects at all, to LAN, left (but not anterior) negativities, right anterior positivities, N400, as well as P600 effects. For example, Allen, Badecker, and Osterhout (2003) examined the incorrect past tense use of English regularly and irregularly inflected verbs in sentence context (e.g., *The man will work/*worked on the platform vs. The man will stand/*stood on the platform*). The grammaticality violations elicited P600 effects for both regular and irregular verbs; and verb surface frequency of both verb types elicited N400 modulations; and an interaction indicated that the grammaticality effect started earlier for irregular than for regular verbs. The authors concluded that the later grammaticality effect was the result of a

Table 1 – Summary of ERP studies on inflection.

Study	Language	Paradigm	Context	Modality	Sample Size	Age range/ mean	Type of Violation	Comparison	Examples	Effects
Allen et al., (2003)	English	violation	sentence	visual	16	–/–	past-tense verb in future context	regular correct versus incorrect	_will work_ versus _*worked_	late positivity (P600), later onset than irregular
					17	–/–		irregular correct versus incorrect	_will stand_ versus _*stood_	late positivity (P600)
Newman et al., (2007)	English	violation	sentence	visual	26	–/–	uninflected verb in past-tense context	regular correct versus incorrect	_Yesterday I frowned_ versus _*frown_	LAN & late positivity (P600)
								irregular correct versus incorrect	_Yesterday I ground_ versus _*grind_	left (posterior) negativity & late positivity (P600)
Penke et al., (1997)	German	violation	sentence story list	visual	20 14 14	21–30/25 22–33/26 22-37/27	incorrect suffix	irregular correct versus incorrect	_aufgeladen_ versus_*aufgeladet_	LAN
								regular correct versus incorrect	_durchgetanzt_ versus_*durchgetanzen_	no effect
Gross et al., (1998)	Italian	violation	sentence	visual	12	22–35/–	incorrect theme vowel & incorrect suffix	irregular correct versus incorrect	_preso_ versus _*prend-a-to_	N400 (lateralized to the right temporal region)
							incorrect theme vowel	irregular correct versus incorrect	_dorm-i-to_ versus _*dorm-a-to_	no effect
							incorrect theme vowel	regular correct versus incorrect	_parl-a-to_ versus _*parl-i-to_	right anterior negativity at temporal sites
Rodriguez-Fornells et al., (2001)	Catalan	violation	sentence	visual	18 (15)	20–29/–	incorrect theme vowel & incorrect suffix	irregular correct versus incorrect	_admès_ versus _*admet_	late positivity
							incorrect theme vowel	irregular correct versus incorrect	_dorm-it_ versus _*dorm-a-t_	left early (not anterior) negativity & late positivity
							incorrect theme vowel	regular correct versus incorrect	_cant-a-t_ versus _*cant-i-t_	late positivity
							incorrect theme vowel	irregular correct versus incorrect	_*tem-a-t_ versus _tem-u-t_	left early (not anterior) negativity & right anterior negativity
Linares et al., (2006)	Spanish	violation	sentence	visual	33	-/21	incorrect stem vowel in irregular forms	irregular correct versus incorrect	_miden_ versus _*meden for stem violation_	LAN & P600 (late positivity)
							incorrect 2nd person instead of 3rd person suffix	irregular correct versus incorrect	_miden_ versus _*mides for suffix violation_	reduced negativity for unmarked form; P600
Regel et al., (2017)	German	violation	sentence	visual	9	-/64	incorrect stem vowel in irregular verbs	irregular correct versus incorrect	_sprach_ versus _*sproch_ _sprach_ versus _*sprech_	N400 & P600; _*sproch_ = _*sprech_

(_continued on next page_)

Table 1 – (continued)

Study	*Language*	*Paradigm*	*Context*	*Modality*	*Sample Size*	*Age range/ mean*	*Type of Violation*	*Comparison*	*Examples*	*Effects*
Morris & Holcomb, (2005)	English	violation	sentence	visual	24 (21)	17–23/20	incorrect suffix & incorrect stem vowel	irregular correct versus incorrect	*brought* versus **bringed*	LAN & late posterior positivity (P600)
							incorrect suffix & incorrect stem vowel	regular correct versus incorrect	*walked* versus **sept (different verbs!)*	LAN & late posterior positivity (P600)
			single words	visual			incorrect suffix & incorrect stem vowel	irregular correct versus incorrect	*brought* versus **bringed*	late (posterior) positivity
							incorrect suffix & incorrect stem vowel	regular correct versus incorrect	*walked* versus **sept (different verbs!)*	late positivity
Smolka & Eulitz, (2015)	German	violation + priming	single words	visual	26	19–36/–	incorrect stem vowel	regular correct versus incorrect	*gekauft* versus **gekäuft*	LAN & N400
							incorrect suffix & incorrect stem vowel	irregular correct versus incorrect	*geworfen* versus **geworft/ *gewurft*	LAN & N400

Study	*Language*	*Paradigm*	*Context*	*Modality*	*Type of Paradigm*	*Sample Size*	*Age range/ mean*	*Comparison*	Examples	Effects
Weyerts et al., (1996)	German	priming	single words	visual	long lag	13	–18–30/–	regular unprimed versus identity	getanzt (unprimed) versus getanzt–getanzt	N400 & post-N400 range
								irregular unprimed versus identity	geboten (unprimed) versus geboten–geboten	N400, later onset than regular
								regular unprimed versus infinitive	getanzt (unprimed) versus tanzen-getanzt	N400 & post-N400 range
								irregular unprimed versus infinitive	geboten (unprimed) versus bieten-geboten	N400, later onset than regular
Münte et al., (1999)	English	priming	single words	visual	long lag	19	18–28/20	regular unrelated versus past tense	walked-stretch versus stretched-stretch	N400 & right fronto-temporal positivity
								irregular unrelated versus past tense	sang-fight versus fought-fight	right centroparietal positivity
Rodriguez-Fornells et al., (2002)	Spanish	priming	single words	visual	long lag	14	20–30/–	regular unrelated versus past tense	ando-lavar versus ando-andar	N400
								irregular unrelated versus past tense	entiendo-querer versus entiendo-entender	no effect
Rastle, Lavric, Elchlepp, and Crepaldi (2015)	English	priming	single words	visual	immediate masked	32	–/24	regular unrelated versus present tense	yolks-wrap versus wraps-wrap	late N400
								irregular unrelated versus present tense	kiss-bear versus bore-bear	(miniscule) N400
Morris and Stockall (2012)	English	priming	single words	visual	immediate masked	20 (17)	18–25/21	regular unrelated versus past tense versus identity	unrelated-walked versus walked-walk versus walk–walk	N250 & N400: past tense = identity
								irregular unrelated versus past tense versus identity	unrelated-drunk versus drunk-drink versusdrink–drink	N250 & N400: past tense = identity; regular = irregular

Leminen & Clahsen, (2014)	German	priming	single words	cross-modal	immediate	24	19–35/24	unrelated versus inflected adjectives versus	frech-sanft versus sanftes-sanft	P300 & N400
Marslen-Wilson and Tyler (1998)	English	priming	single words	cross-modal	immediate	–	young adults	regular unrelated versus past tense	locked-jump versus jumped-jump	N400 & LAN
								irregular unrelated versus past tense	shows-find versus found-find	N400 & LAN
Justus et al., (2008)	English	priming	single words	auditory	immediate	16	–/25	regular unrelated versus past tense	worked-seem versus looked-look	N400 & late N400
								suffixed irregular: unrelated versus past tense	had-fight versus slept-sleep	N400 & late N400
								vowel change irregular: unrelated versus past tense	bound-wake versus spoke-speak	N400 & late N400: vowel change > suffixed > regular
Justus et al., (2009)	English	priming	single words	cross-modal	immediate	16	–/24	regular unrelated versus past tense	worked-seem versus looked-look	N400
								irregular: unrelated versus past tense	bound-wake versus spoke-speak	N400, regular = vowel change irregular
								pseudopast: unrelated versus related	unrelated versus field-feel	late positive component (LPC)
Kielar and Joanisse (2009)	English	priming	single words	visual	immediate unmasked	14	17–33/24	regular unrelated versus past tense	rented-walk versus walked-walk	N400
								suffixed irregular: unrelated versus past tense	wept-feel versus felt-feel	N400
								vowel change irregular: unrelated versus past tense	sang-write versus wrote-write	N400: regular > suffixed > vowel change
			single words	cross-modal	immediate	15	19–30/24	regular unrelated versus past tense	rented-walk versus walked-walk	N400: regular > suffixed > vowel change
								suffixed irregular: unrelated versus past tense	suffixed irregular: wept-feel versus felt-feel	N400
								vowel change irregular: unrelated versus past tense	vowel change irregular: sang-write versus wrote-write	N400
Smolka et al., (2013)	German	priming	single words	visual	immediate unmasked	19 (15)	19–31/–	regular unrelated versus participle	trockne-lerne versus gelernt-lerne	N400: regular > semi-irregular > vowel change
								semi irregular: unrelated versus participle	winke-backe versus gebacken-backe	N400
								vowel change irregular: unrelated versus participle	fahnde-trinke versus getrunken-trinke	N400

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Table 1 — (continued)

Study	Language	Paradigm	Context	Modality	Type of Paradigm	Sample Size	Age range/ mean	Comparison	Examples	Effects
Smolka & Eulitz, (2015)	German	priming	single words	visual	immediate unmasked	26	19–36/–	semantic priming versus participle priming	gekocht-backe versus gebacken-backe	early N400
								regular unrelated versus participle	gehüpft-kaufen versus gekauft-kaufen	LAN & N400
								irregular unrelated versus participle	geholfen-werfen versus geworfen-werfen	LAN & N400: regular = irregular
Pulvermüller, Härle, and Hummel (2001)	German	unprimed	single word	visual		20	18–32/23	face-related versus arm-related versus leg-related	bite versus draw versus kick	P300: face > arm > leg
Lehtonen et al., (2007)	Finnish	unprimed	single word	visual		16	21–29/25	monomorphemic versus inflected	kissa versus koirassa	N400
Leminen et al., (2013)	Finnish	oddball		auditory	passive listening	15	21–43/29	inflected versus derived	juustoa versus työtön	MMN: inflected > derived

computationally demanding parsing process for regular verbs, where the suffix independently encodes tense information in addition to the lexical meaning information provided by the stem. In a similar design (Newman, Ullman, Pancheva, Waligura, & Neville, 2007), participants saw uninflected regular or irregular verbs in sentence contexts that required regular or irregular past tense forms (e.g., *Yesterday I frowned/*frown at Billy vs. Yesterday I ground/*grind up coffee*). Regular violations elicited a LAN, whereas irregular violations induced a left posterior negativity in comparison to correct past tense forms. Both regular and irregular violations elicited later positivities (P600) that were similar in time course and scalp distribution. In spite of nonsignificant interactions between regularity and violation in any of the regions of interest, the authors interpreted the LAN for regular (but not for irregular) violations to indicate “the existence of at least partially distinct neurocognitive processes in the processing of the two verb types” (Newman et al., 2007, p. 441).

Various studies compared correct with violated past tense or participle forms in German (Hahne, Müller, & Clahsen, 2006; Penke et al., 1997; Regel, Kotz, Henseler, & Friederici, 2017), Italian (Gross, Say, Kleingers, Clahsen, & Münte, 1998), Catalan (Rodriguez-Fornells, Clahsen, Lleo, Zaake, & Münte, 2001), and Spanish (Linares, Rodriguez-Fornells, & Clahsen, 2006). The results across studies are very inconclusive, because—contrary to the expectations—the violated forms of both regular and irregular inflection induced not only LAN and P600 effects, but also null effects, left (but not anterior) negativities, right anterior negativities, and N400 effects (for a summary of the effects see Table 1). Also several violation studies on German plurals found many different patterns for the different (*-s*, *-(e)n*, *-e*, *-er*, and zero-suffix) plural violations (e.g., Bartke, Rösler, Streb, & Wiese, 2005; Lück, Hahne, & Clahsen, 2006; Weyerts, Penke, Dohrn, Clahsen, & Münte, 1997; Winter, Eulitz, & Rinker, 2014). Unfortunately, these heterogeneous ERP effects were not reflected in the interpretation of the studies, which mostly followed the dual-mechanism tradition and focused on a categorical processing difference between regular and irregular verb inflection and plural formation.

2.1.2. *The priming paradigm*

In the priming paradigm, the time course of complex word processing is assumed to be reflected in N250 and N400 effects. Both reflect early stages of lexical processing: the former the mapping of orthographic representations onto whole-word orthographic representations, and the latter reflect the subsequent mapping of lexical form onto meaning. Traditionally, the N400 effect has been interpreted to be an index of facilitated lexical access of a word relative to its unprimed presentation (e.g., Bentin & Peled, 1990; Lau, Almeida, Hines, & Poeppel, 2009; Lau, Phillips, & Poeppel, 2008; Rugg, 1990), or as the access of conceptual knowledge associated with a word (Federmeier, 2007; Kutas & Federmeier, 2000; Van Petten & Luka, 2006), while others interpret it as an index of post-lexical processes, including semantic integration (Hagoort, 2008).

In the Chomskyan tradition, early EEG studies provided evidence for distinct patterns of processing for regular and

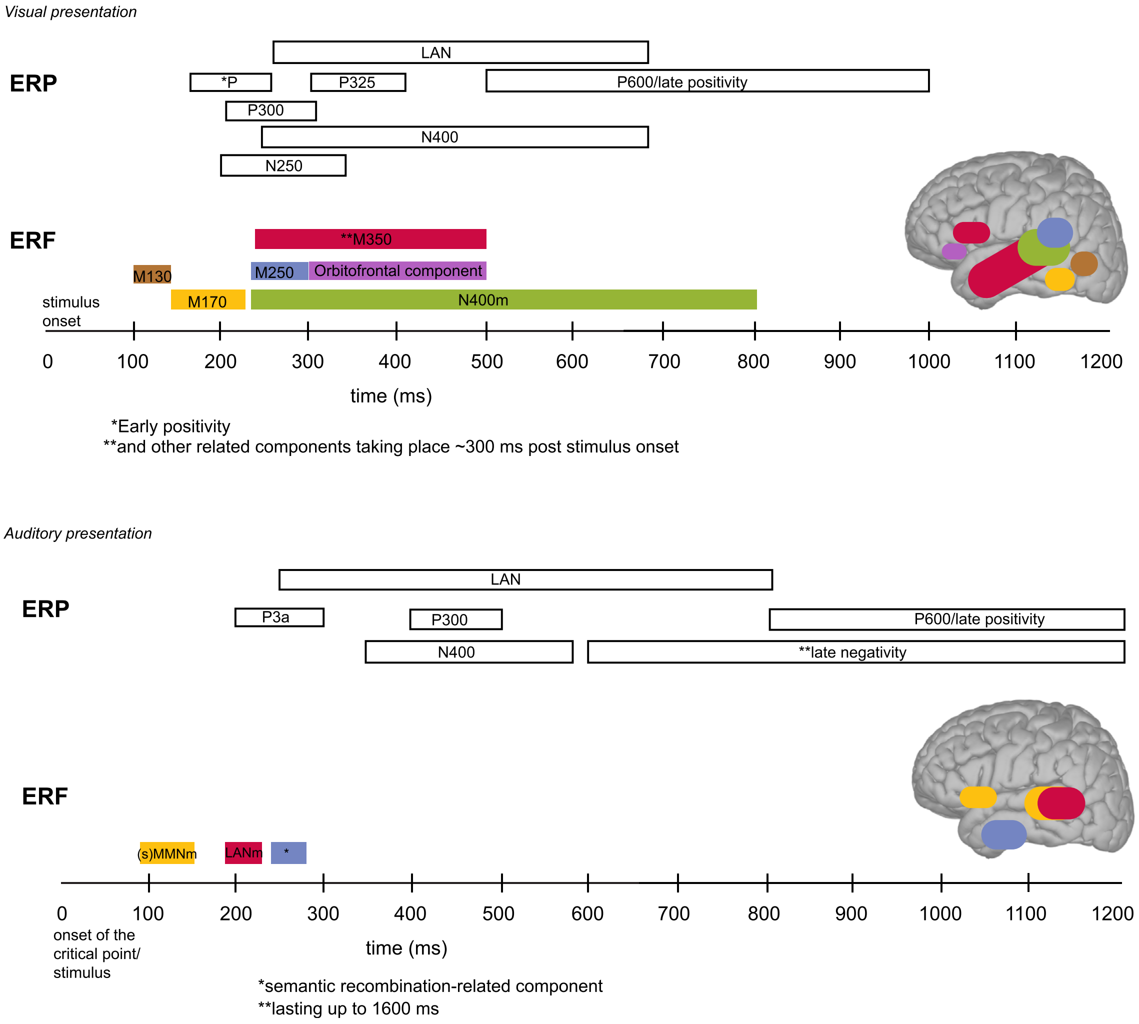

Fig. 1 – A schematic representation of the event-related potentials and fields (ERP and ERF, respectively) associated with morphological processing and their timing (in msec), for visual (above) and auditory (below) presentation. The exact latencies of the components tend to differ across different studies and here, the time-windows of the components take into account the inter-study variation. For ERF components, the colored boxes depict their reported neural sources (on a template brain).

irregular verbs in German (regular *tanzen-getanzt vs.* irregular *bieten-geboten*; Weyerts, Münte, Smid, & Heinze, 1996), English (*stretched-stretch vs. fought-fight*; Münte, Say, Clahsen, Schiltz, & Kutas, 1999), and Spanish (regular *stretched-stretch vs.* irregular *entiendo-entender*; Rodriguez-Fornells, Münte, & Clahsen, 2002,[2]): When compared to baseline (i.e. unprimed or unrelated) conditions, regular verbs showed a reduction in the N400 range, in one study the N400 reduction was accompanied by a right frontotemporal positivity (Münte et al., 1999). In contrast, irregular verbs showed either an N400 deflection that occurred ~100 msec later than that by regular verbs (e.g., Weyerts et al., 1996), a right centroparietal positivity as compared to a right frontotemporal positivity elicited by regular verbs (Münte et al., 1999), or no effect at all (Rodriguez-Fornells et al., 2002). In line with dual-mechanism hypotheses, the N400 effects were taken as evidence that regular inflection is morphologically decomposed and the unmarked base forms are directly accessed; the lack of N400 effects was taken as indication that the lexical entries of irregular inflection differ from their corresponding base forms, which are accessed only indirectly (see Rodriguez-Fornells et al., 2002, p. 448). Other effects were typically left unexplained.

By contrast, authors who do not follow the dual-mechanism approach observed equivalent N400 effects in an auditory prime-target design (Justus et al., 2011) or equivalent LAN and N400 effects in a visual prime-target design elicited by regular and irregular past tense priming in English. Furthermore, these N400/LAN effects elicited by morphological relatedness differed from the N400 effect by purely semantically related words (Marslen-Wilson & Tyler, 1998) or by orthographically overlapping word pairs with respect to their polarity/distribution (Justus et al., 2011).

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[2] Note that this study used an unrelated target as baseline and not, as usual, an unrelated prime.

Further studies on regular and irregular verb inflection in English tested whether approaches originally developed for derivational processes can be generalized to inflectional word processes, that is, whether morpho-orthographic decomposition runs in parallel or precedes meaning computation (*form-with-meaning* or *form-then-meaning account*, respectively). Applying masked priming, Morris and Stockall (2012) observed equivalent N250 and N400 priming effects for both regular and irregular inflections. The early N250 effects argue for a rapid, form based morphological decomposition of all morphologically complex word forms (derivations; regular and irregular inflections), supporting early stages of form-based pre-semantic processing. Since irregular inflections do not involve linearly adjacent affixes, the early word recognition processes are sensitive to patterns associated with both regular and irregular allomorphy.

By contrast, another priming study (Rastle, Lavric, Eichlepp, & Crepaldi, 2015) reported a miniscule N250 (the magnitude of the effect was only .5 μV or less at left frontal and right posterior electrodes) and subsequent N400 effect for regular inflections. This was taken to indicate that regular stems overlap at the early morpho-orthographic level and at the lexical-semantic level of representation. In addition, a weaker small-scale N400 effect, occurring ~40 msec later for irregular (than for regular) inflection purportedly indicated that the stems of irregular inflections overlap only at the later lexical-semantic level of representation. In lack of significant effects for irregular inflections, the N400 modulation by regular inflections had a substantially earlier onset and greater magnitude.

As soon as more recent studies compared more than two verb types, graded rather than binary brain responses emerged. Three studies in English (Justus, Yang, Larsen, de Mornay Davies, & Swick, 2009; Justus et al., 2008; Kielar & Joanisse, 2009) and one in German (Smolka et al., 2013) compared the priming by regular verbs (English *learned-learn*; German *gelernt-lerne*), weak/suffixed irregulars (English *spent-spend*; German *gelaufen-laufe*), and strong/vowel-change irregulars (English *spoke-speak*; German *gesprochen-spreche*). In all four studies, all three verb types showed a) N400 reductions for primed targets relative to unprimed targets, b) graded ERP effects between the verb regularities, c) intermediate effects by weak/suffixed irregular verbs. Under visual priming (Justus et al., 2008), strong/vowel-change irregular verbs induced the strongest N400 effects, and regular verbs the weakest. Moreover, under cross-modal priming (Justus et al., 2009), strong/vowel-change irregular verbs and regular verbs induced equivalent N400 effects, while pseudopast (e.g., *field-feel*, *bide-buy*) and form-related pairs (e.g., *barge-bar*) induced a late positive component (LPC).

In cross-modal priming study by Kielar and Joanisse (2009) and in the visual priming study by Smolka et al. (2013), regular verbs induced the strongest N400 facilitation, weak/suffixed irregulars an intermediate effect, and strong/vowel-change irregulars the weakest facilitation. The authors of these studies concluded that there was no evidence for a categorical distinction between 'regular' and 'irregular' verbs. On the contrary, the data are more consistent with single-system accounts: either connectionist (e.g., Kielar & Joanisse, 2009) or the stem-based accounts (Smolka et al., 2013).

To date, there is a single study that combines the violation and the priming paradigm. Smolka and Eulitz (2018) contrasted the N400 priming effects by regular/irregular German participles with those of nonwords, which comprised illegal combinations of regular/irregular stems with regular/irregular suffixes (e.g. **gekäuft*, **gewurft*). The N400 priming effects by nonword participles (**gewurft-werfen*, '**threwed-throw*') were equivalent to those by existing participles (*geworfen-werfen*, '*thrown-throw*'). Since nonwords are non-existent and hence, not stored in lexical memory, their stems must have been accessed to yield priming on the base verbs. These findings were taken to indicate that both regular and irregular stems are accessed (cf. Clahsen, Prüfert, Eisenbeiss, & Cholin, 2002, for the notion that irregular stems are inaccessible) and that all stems are processed by the same neurocognitive system.

Another cross-modal priming study focused not on the difference between regular and irregular inflection but on the effects of lexical-semantic and morpho-syntactic relatedness of affixes. Leminen and Clahsen (2014) investigated German inflected adjectives and found that lexical-semantic priming (e.g., *sanftes-sanft* 'soft') showed a reduced N400 for lexically related primes and targets, as compared to unrelated ones (*frech-sanft* 'naughy-soft'). In contrast, prime-target overlap with respect to morphosyntactic features (e.g., *sanftes-sanfte*; *sanftem-sanfte vs. sanfte–sanfte*) yielded a reduced positivity in the 200–300 msec time-window, as compared to the identity control (*sanfte–sanfte*). The reduced early positivity was taken to reflect facilitation of grammatical processing effort in case of primed morpho-syntactic target features, while the reduced N400 was taken to index facilitation in lexical retrieval for primed words. Since the ERP pattern showed differences in onset latencies between morpho-syntactic and lexical-semantic processing, it was interpreted to be consistent with structure-first models of language processing.

2.1.3. *Unprimed lexical decisions*

Two studies on Finnish, using visual and auditory lexical decision tasks (Lehtonen, Cunillera, Rodriguez-Fornells, Hulten, Tuomainen, & Laine, 2007; Leinonen et al., 2009), reported increased N400 effect for inflections as opposed to monomorphemic words. Both studies suggested evidence for the so-called morphological processing cost of combining the stems and suffixes in order to provide a meaning of the morpheme combination (Laine, Niemi, Koivuselkä-Sallinen, Ahlsén, & Hyönä, 1994).

A different approach was chosen by Pulvermüller, Haerle, and Hummel (2001) who studied the processing of action verbs. Participants made lexical decisions to verbs that were face-related (e.g., *bite*, *smile*), arm-related (e.g., *push*, *draw*), or leg-related (e.g., *kick*, *walk*). A P300-like (400–500 msec) amplitude was highest (most negative-going) for face-related verbs and lowest (most positive-going) for leg-related verbs. Further grand-average current source density curves (CSDs) indicated CSD enhancement at left-lateral cites for face-related verbs and at central cites for leg-related verbs and were interpreted to reflect the homuncular organization of the motor cortex. The results were taken to support associative theories that the cortical distribution of cell assemblies reflect the words' meanings.

Table 2 – Summary of MEG studies on inflections. The studies used single word tasks.

Study	Language	Task	Modality	Sample size	Age range/mean age	Grammatical category	Comparison	Effects and their neural sources
Whiting et al., 2013	English	Passive listening	Auditory	15	19-34	Verb	Inflections, derivations, pseudoaffixed words	MMN, left fronto-temporal areas
Bakker et al., 2013	English	Passive listening	Auditory	23	18-30	Verb	Grammatical > Ungrammatical inflections (LF/HF[a]), Pseudowords	sMMN, Left temporal, inferior-central, and inferior-frontal areas
Stockall & Marantz, 2006	English	Lexical decision (priming)	Visual	17 (Exp 1); 13 (Exp 2)	19-33 (Exp 1),24-48 (Exp 2)	Verb	Regular past tense> Irregular past tense, Irregular > regular (high and low overlap) Inflected > Simple Inflected > Derived	M350, no source localization
Leminen et al., 2011	Finnish	Acceptability judgment	Auditory	10	18-34	Noun	Regular > Irregular > Pseudo-irregular > Identity	N400m, LANm, left superior temporal area M170, M350, Left middle temporal, Left middle-anterior fusiform, Inferior temporal ROIs[b]
Fruchter et al., 2013	English	Lexical decision (masked priming)	Visual	16	not reported	Verb	Inflected words > Simple words (HF and LF)	N400m, left superior temporal cortices
Vartiainen et al., 2009	Finnish	Lexical decision	Visual	10	25-46	Noun		

[a] HF high frequency, LF: low frequency.
[b] ROI: region of interest.

2.1.4. *Mismatch negativity (MMN)*

Using a task-free passive auditory oddball paradigm, Leminen, Leminen, Kujala, & Shtyrov (2013) investigated automatic processing of inflected and derived real words and matched complex pseudowords. For inflections, the authors observed smaller MMN responses than to derived words, which were taken to reflect early automatic parsing of inflected words as opposed to a possible dual-route processing of derivations. The results for inflections were interpreted to be in line with ERP studies using attentive reading/listening paradigms (lexical decision and acceptability judgment) with Finnish (e.g. Lehtonen et al., 2007; Leinonen et al., 2009), all in favor of decompositional processing of Finnish inflected words.

2.2. *MEG*

Like EEG, magnetoencephalography (MEG) directly registers mass electrical activity of neuronal populations, and is able to provide the temporal resolution on the millisecond scale. This allows for the mapping of the neural activation underlying the morphological processing online. In addition, MEG has a spatial resolution of approximately 3 mm, due to a high-density coverage with a large number of different sensors (up to 306 channels). A handful of MEG studies have focused on inflected words to track down the spatiotemporal dynamics of morphological decomposition. Table 2 summarizes available MEG studies, most of which attempted to find neural signatures of morphological decomposition. In the MEG literature, particularly with visual stimuli, the frequently reported components have been the M170, the M350, as well as the N400 m. Within the field of morphology, the M170 has been taken to reflect early index of form-based morphological decomposition (Zweig & Pylkkänen, 2009). The M350/N400 m effects have been related to, for instance, lexical access and morphological decomposition (Fiorentino & Poeppel, 2007; Pylkkänen, Feintuch, Hopkins, & Marantz, 2004). For more discussion on the nature of the N400(m) effect, see previous EEG section.

Using English past tense inflections as stimuli, with priming techniques, two studies specifically aimed at obtaining evidence for the account that all morphologically related forms activate their roots equally in the early stages of lexical activation (Full Decomposition Account) – hence, addressing the "past-tense" debate. An earlier study (Stockall & Marantz, 2006) used overt priming on irregular (e.g., *teach-taught*; *taught-teach*; *give-gave*; *gave-give*) and regular verbs (*jump-jumped*), both of which produced M350 priming effects, which was taken to support the full decomposition account. No effects earlier than M350 were observed. More recently, Fruchter et al. (2013) reported a significant masked morphological priming effect for the irregular verbs, seen in the modulation of the M170. This was taken to support the earlier findings by Stockall and Marantz (2006), as providing further evidence for the early decomposition of irregular verbs. The authors also reported of a presence of the M350 but did not discuss them in detail. Using an unprimed lexical decision task combined with MEG, Vartiainen, Aggujaro, Lehtonen, Hulten, Laine, and Salmelin (2009) reported stronger and longer-lasting activation of the left superior temporal cortex for Finnish inflected nouns. Increased activation for inflected as opposed to monomorphemic words took place in the 200–800 msec time-window (after the stimulus onset), thus resembling the N400 m effect. Since no earlier, M170-like effects, were observed, this was taken as support for the view that morphological processing cost for inflected words stems from the later semantic–syntactic level rather than from early decomposition (Laine et al., 1994).

The reading studies described above interpreted their findings as favouring morphological decomposition, but it is still unclear in which time frame morphological parsing takes place. Studies with auditory modality might play an important role in resolving the precise timing issue, since they are able to track the processing as the stimulus unfolds. MEG studies using auditory stimuli have used both passive and active listening. Passive listening paradigms are instrumental to reveal automatic processes involved in morphological decomposition, since they remove attentional and strategic effects, and are specific to linguistic information type (Hanna, Shtyrov, Williams, & Pulvermüller, 2016). Using passive auditory oddball paradigm and addressing the past-tense debate, Bakker, Macgregor, Pulvermuller, and Shtyrov (2013) found that overregularized forms (*flied*) elicited an automatic neurolinguistic response pattern, repeatedly observed for asyntactic as opposed to syntactic structures (Hanna et al., 2014; Hasting & Kotz, 2008; Pulvermüller & Shtyrov, 2006; Shtyrov, Pulvermüller, Näätänen, & Ilmoniemi, 2003). This pattern has been suggested to reflect combinatorial processing of syntactic structures, now extending also to inflections (for similar findings with EEG, see Leminen et al., 2013). Importantly, such response pattern was not observed for simplex words contrasted with pseudowords, which showed a reversed effect i.e. 'lexical' response pattern (Garagnani, Shtyrov, & Pulvermüller, 2009). These automatic neural responses were yielded as early as 100–150 msec after the onset of the critical information. Hence, this finding supported the view that regular inflections are generated combinatorially, even without focused attention on the stimuli. This result pattern was further corroborated by findings obtained with a similar paradigm (Whiting, Marslen-Wilson, & Shtyrov, 2013), which showed that unattended processing of English verb and noun inflections yielded early (135 msec after the onset of the critical information) activation of the left fronto-temporal language regions. Early (~100 and 200 msec) increased left superior temporal responses for spoken inflected words have also been observed with an active listening paradigm (acceptability judgment) (Leminen et al., 2011). The early ~100 msec activation was interpreted to reflect lexical access to a suffix, irrespective of its category. The later (~200 msec), larger left-lateralized negativity for the inflected as compared to the derived and simple words was taken to reflect the analysis of the base and suffix, and, possibly, evaluation of the (morpho)syntactic features of the morpheme combination. It should be noted, however, that when including multi-item ($N = 80$) inflected word sequences to a passive listening paradigm, no ~200 msec increase in activation was observed for inflections, despite time-locking to a critical point (Leminen, Lehtonen, et al., 2013). This implies that with a non-oddball paradigm and a large number of different stimuli, despite matching by lexical and acoustic factors, inflectional

Table 3 – Summary of fMRI studies on inflection. All studies used single word tasks. Only findings related to morphological decomposition are reported.

Production tasks

Study	Language	Task	Modality	Sample size	Age range/ mean age	Grammatical category	Comparison	Activated brain regions
Beretta et al., 2003	German	Covert generation of the inflected form	visual	8	24–45	verbs & nouns	Irregular > Regular Regular > Irregular	B: Broca's and Wernicke's areas L: MFG, SMG and STG
Joanisse & Seidenberg, 2005	English	Overt generation of the inflected form	auditory	10	22–32	verbs	Regular > Irregular	BIL: IFG, MTG, ITG
de Diego-Balaguer et al., 2006	Spanish	Covert generation of the inflected form or covert repetition of the stem	visual	12	$M = 23$	verbs	Regular Inflection > Repetition Irregular Inflection > Repetition	L: IFGoperc, cerebellum R: parahippocampal gyrus, sensorimotor cortex L: MFG, IFG, cerebellum; R: sensorimotor cortex
Desai et al., 2006	English	Overt generation of the inflected form or overt repetition of the stem	visual	25	20–47	verbs	Regular Inflection > Repetition	L: PCG, IFG, MFG, SMG, IPS, PUT, GP R: IFG, PCG, aINS, IPS BIL: SMA, CG, ITG, FG, STG
							Irregular Inflection > Repetition	L: PCG, IFG, MFG, SMG, IPS, PUT, GP R: IFG, PCG, aINS, IPS BIL: SMA, CG, ITG, FG, STG, THAL, CN
							Irregular Inflection > Regular Inflection	L: SMG, FG, ITG R: aINS BIL: IFG, MFG, PCG, IPS, BG
							Regular Inflection > Irregular Inflection	L: STG, PT R: SMG
Marangolo et al., 2006	Italian	Overt generation of the inflected form or overt repetition of the stem	auditory	10	21–29	verbs, adjectives & nouns	Verb Inflection > Repetition Adjective Inflection > Repetition Noun Inflection > Repetition	L: IFGtri, IFGoper, MFG, PCG, IPL, SPL, AG, SMA, ITG L: PCG, MOG, AG R: MFG, SOG, MOG L: INS R: AC, MC, STG
Sahin et al., 2006	English	Cued covert production (overt and zero inflections) or covert repetition	visual	18	18–25	verbs & nouns	Overt inflection > Repetition Zero inflection > Repetition Overt inflection > Zero inflection	L: IFG, INS and SMA L: IFG, PCG, MFG L: IFG, INS, SMA, AG, PG
Oh et al., 2011	English	Overt generation of the inflected form or overt repetition of the stem	visual	19	23–48	verbs	Regular Inflection > Irregular Inflection Irregular Inflection > Regular Inflection	L: MFG, IFG, CN, MTG, IPL R: MFG, IFG L: HIP, CER, FG, MTG R: MFG, SFG, MTG, CER, IPL, STG, Precuneus
Slioussar et al., 2014	Russian	Overt generation of the inflected form	visual	21	19–32	verbs & nouns	Regular Inflection > Irregular Inflection Irregular Inflection > Regular Inflection	L: IPL, IFG, PCG, MFG R: SPL, AG, IPL, SMG, CER L: PCG, MFG, IFG, IPL, SPL, INS, CER, SMA R: CER
Kireev et al., 2015	Russian	Overt generation of the inflected form	visual	21	19–32	verbs & nouns	Regular Verbs > Irregular Verbs	Increased connectivity between L IFG and BIL STG

(*continued on next page*)

Table 3 – (*continued*)

Production tasks

Study	Language	Task	Modality	Sample size	Age range/ mean age	Grammatical category	Comparison	Activated brain regions
Nevat et al., 2017	Artificial	Overt generation of the inflected form or overt repetition of the stem	auditory	17	20–47[a]		Regular Inflection > Repetition	L: CN, IFG, PCG, SOG, MOG, SMA, MFG, CG, Precuneus R: CN BIL: CER, occipital cortex

Comprehension tasks

Study	Language	Task	Modality	Sample size	Age range/mean age	Grammatical category	Comparison	Activated brain regions
Davis et al., 2004	English	1-back synonym-monitoring task	visual	11	18-40[a]	verbs	Inflected > simple verbs	No effects
Tyler et al., 2004	English	semantic similarity judgement	visual	12	20–33	inflected verbs and nouns	Inflected verbs/ nouns > baseline letter strings	L: Parahipp., FG, IFG, MFG, THA, CN R: PCG, CG, CER, IFG
Tyler et al., 2005	English	phonological similarity judgement	auditory	18	*M* = 24, SD = 7	verbs	Regular inflection > Irregular inflection	L: HG, MTG, CG, IFG R: STG
Lehtonen et al., 2006	Finnish	unmasked lexical decision	visual	12	21–29	nouns	Inflected > simple	L: IFG, ITS, STS
Yokoyama et al., 2006	Japanese	unmasked lexical decision	visual	28	18–26	verbs	Inflected > simple	L: IFG, premotor area
Lehtonen et al., 2009	Finnish & Swedish	unmasked lexical decision	visual	16	*M* = 26.3, SD = 3.42	nouns	Finish: Inflected > simple Swedish: Inflected > simple	L: IFG, MTG No effects
Bozic et al., 2010	English	auditory gap detection	auditory	12	Not reported	verbs	Inflected > simple	L: IFG, STG, temporal pole
Szlachta et al., 2012	Polish	passive listening with 1-back memory task	auditory	21	18-33[a]	nouns	Inflected > simple Inflected > acoustic baseline	No effects L: IFG BIL: MTG, STG, temporal pole
Pliatsikas et al., 2014	English (native and nonnative speakers combined)	masked priming with lexical decision	visual	36	19-38[a]	verbs	Regular inflection > Irregular inflection	L: IFG. CN R: CER, CN
Bozic et al., 2015	English	passive listening with 1-back memory task	auditory	18	Not reported	verbs & nouns	Inflected > simple	L: IFG, STG, ITG
Klimovich-Gray et al., 2017	Russian	active listening with 1-back memory task	auditory	20	19–39	verbs	Inflected > simple Inflected > acoustic baseline	L: STG, MTG R: STG L: MTG, STG, INS, IFG, PCG, SMA R: STG
Prehn et al., 2018	German	grammaticality judgment	visual	20	51–87	verbs	Regular > Irregular	L: MFG, DLPFC

[a] Age range for the original sample of these studies. The Ns reported here are after participant exclusions. No age range reported for the samples after the exclusions.

processing cost reflected in the later (~200 msec) time-frame is either temporally smeared or is partly attention-dependent.

Taken together, all MEG studies on inflection interpret their findings as evidence for morphological decomposition. The findings with spoken words are more convergent, however, which may be due to a similar type of analysis (time-locking the responses to the critical point). While admittedly still scarce, the majority of the emerging findings on spoken words suggest that combinatorial processing of inflections take place in the left fronto-temporal cortices prior to 250 msec after the onset of the critical information. With regards to visual inflected word processing, the studies using overt priming and lexical decision have reported the modulations of the M350/N400 effect, with the earliest (<200 msec) effects seen only with the masked priming paradigm.

2.3. *(f)MRI*

Compared to the other two morphological operations (derivation and compounding), inflection has been a very well-known and studied operation with fMRI. fMRI studies on inflectional morphology have focused on the localization in the brain of inflectional processing, aiming to explain whether the proposed linguistic operations (e.g. rule-based (de-)composition of regularly inflected forms) have their correlates in brain activation, and which brain regions might undertake them. The available fMRI studies are presented in Table 3, and Fig. 2 illustrates the brain regions most commonly reported in the fMRI literature (including for processing of derivations and compounds). It is worth noting that, as for the other methods, the field has been dominated by studies on English inflection, and most commonly verbal inflection, with only a few studies looking at nouns.

The earliest available studies were generally inspired by, and mostly focused on, the English past tense debate. A significant number of fMRI studies, with a variety of tasks, provided evidence for distinct patterns of processing for regular and irregular past tense forms in English: more specifically, when compared to baseline conditions (e.g., letter strings or other non-word stimuli), in general both types of inflection appear to activate an extended network in the left hemisphere, and especially temporal and parahippocampal regions. However, when directly compared to irregular inflection, regular inflection appears to engage additional areas such as the left IFG and MFG, the basal ganglia and the cerebellum (Bozic, Fonteneau, Su, & Marslen-Wilson, 2015; Bozic et al., 2010; Davis, Meunier, & Marslen-Wilson, 2004; Desai, Conant, Waldron, & Binder, 2006; Joanisse & Seidenberg, 2005; Oh, Tan, Ng, Berne, & Graham, 2011; Pliatsikas, Johnstone, & Marinis, 2014; Sahin, Pinker, & Halgren, 2006; Tyler, Bright, Fletcher, & Stamatakis, 2004; Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005). Of these areas, the most consistently activated appear to be the LIFG and its various subcomponents, often accompanied by the basal ganglia and the cerebellum. Similar patterns have been observed for the processing of complex nouns (plural forms) in the few studies where these were examined (Bozic et al., 2015; Sahin et al., 2006; Tyler et al., 2004). Conversely, irregular infection is less often reported to increase activation of certain brain regions compared to regular inflection, and when this is reported, these regions tend to include temporal, parietal and parahippocampal areas, although the available evidence is less consistent. It also worth noting that similar patterns have been largely reported in the few available studies in German, a language that is typologically and morphologically close to English (Beretta et al., 2003; Prehn, Taud, Reifegerste, Clahsen, & Flöel, 2018).

The evidence from English (and German) has highlighted the central role of the LIFG in the processing of regular inflection, which has been linked to its documented role in performing syntactic operations (Ullman, 2004), suggesting that inflection (at least regular) should also be considered a grammatical operation with clear correlates in brain activity. In this vein, the observed distinction between regular versus irregular inflection at the brain level is supportive of the idea of a dual route in the processing of past tense inflection (Pinker & Ullman, 2002), although a few researchers have argued for single-route processing (Desai et al., 2006; Joanisse & Seidenberg, 2005). Moreover, the selective activation by regular inflections of a network involving the LIFG, basal ganglia and the cerebellum, also characterized as the procedural memory network (Ullman, 2004), further reinforced the idea of automated, rule-based implicit processing of regular inflections. This is in contrast to whole-word learning and

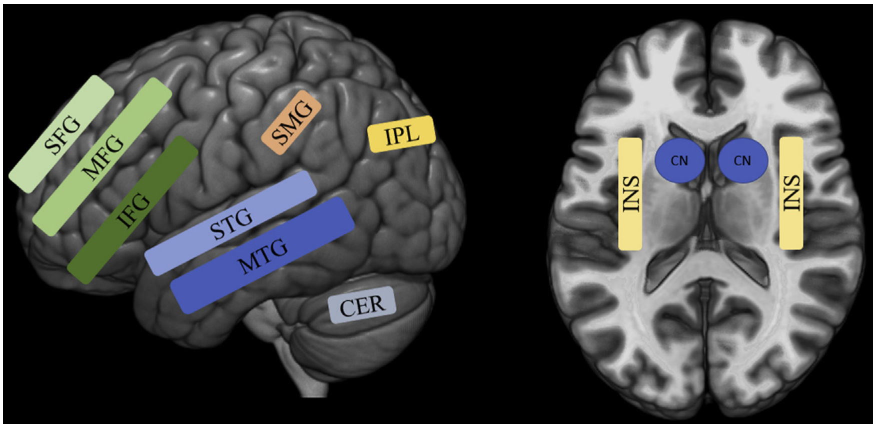

Fig. 2 – Brain regions most commonly reported in the fMRI literature on morphological processing. All effects are bilateral.

retrieval of irregular inflections, which are expected to engage a temporal-hippocampal network (characterized as the declarative memory network) in a similar way as regular inflections, in the sense that both types of inflection require the retrieval of lexical stems.

As clearly defined as this pattern may seem, it remains incomplete and possibly inadequate to reflect inflectional processing in the brain. The main reason for that is that the dual-route processing accounts, in both their behavioral and neurocognitive versions, are heavily based on English, a language with only two verb classes (regular and irregular), of which irregular verbs are not considered a productive class. Therefore, these accounts might not be readily applicable to morphological operations in languages with multiple productive verb classes (e.g. Russian) or languages that combine suffixation and (optional) prefixation for inflection (e.g. Greek) or languages that inflection is not carried out by serial concatenations of morphemes (e.g. Arabic). Thus, evidence from other languages is invaluable in helping us describe the brain mechanisms underlying decomposition and better understand the constraints that apply, including uncovering those rules and/or constraints that apply universally. However, the available evidence remains scarce and mixed. This could either be due to the scarcity of the research itself, with single studies from a variety of languages and with a variety of tasks producing results that do not fit into a consistent pattern, or due to real linguistic differences between English and other languages, which makes them less comparable. For example, in Italian it has been shown that, while producing inflected verbs engages the LIFG, producing inflected adjectives activates regions such as the left precentral, left angular and bilateral middle occipital gyri, whereas producing inflected nouns activates the left insula and several structures in the right hemisphere (Marangolo, Piras, Galati, & Burani, 2006). Moreover, evidence from Spanish (de Diego-Balaguer et al., 2006) has revealed differences in the LIFG activation for regular and irregular verbs, but increased activity of bilateral frontal regions for irregular verbs and left temporal/hippocampal regions for regular verbs, a pattern that is incompatible, if not opposite, to the findings from Germanic languages. Moreover, studies in Finnish have shown both left frontal and temporal activations for processing of regular inflections versus simple stems (Lehtonen et al., 2009; Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006), whereas a similar comparison revealed activations of the left premotor area along with the LIFG in Japanese (Yokoyama et al., 2006). No similar effects have been reported in Polish (Szlachta, Bozic, Jelowicka, & Marslen-Wilson, 2012), where LIFG and bilateral temporal activations were only revealed when inflected forms were compared to an acoustic baseline, or Swedish, where it was even suggested that morphologically complex forms are processed as whole words (Lehtonen et al., 2009). Of particular interest is Russian, where the available studies have generally shown similar patterns of activity for regular and irregular verbs, with some researchers suggesting that morphologically complex forms in Russian are always decomposed irrespective of their regularity (Kireev, Slioussar, Korotkov, Chernigovskaya, & Medvedev, 2015; Klimovich-Gray, Bozic, & Marslen-Wilson, 2017; Slioussar et al., 2014). Finally, a recent study using an artificial language reported a widespread bilateral network of regions involved in the processing of complex rule-based inflection (Nevat, Ullman, Eviatar, & Bitan, 2017).

More recently, several researchers have used *structural* MRI methods in an attempt to link the acquisition of morphology by non-native speakers of a language to restructuring of those brain regions that are thought to subserve morphological processing. This is based on suggestions that the acquisition of a non-native language (especially later in life than the native language) is accompanied by significant restructuring of brain regions related to language processing (Pliatsikas, in press). This might be of particular relevance to the acquisition of grammatical rules, such as the past tense inflection rule in English, since it has been suggested that learning and applying rules in a second language (L2) is a demanding and potentially unachievable task (Clahsen & Felser, 2006). In this light, Pliatsikas, Johnstone, and Marinis (2014) showed that the volume of the cerebellar grey matter in Greek L2 learners of English correlated positively with how fast they performed lexical decisions in a masked priming task, but only when regularly inflected forms, and not irregular ones, were processed as primes. This suggested that the cerebellum, which has already been shown to be involved in processing of regular morphology (Pliatsikas et al., 2014), needs to restructure in order to accommodate the acquisition of a new grammatical rule, and the degree of restructuring correlated with how efficiently the rule was applied. However, Prehn, Taud, Reifegerste, Harald, and Flöel (2018) recently failed to replicate this effect, but this could be due to a number of differences between the two studies (different L2s, different experiences of the bilingual groups etc.). It is obvious that the use of structural MRI to explain the acquisition and/or processing of morphology is still at its infancy; however, it might prove a useful source of understanding the relevant processes, especially since the acquisition of anatomical images is part of the standard protocol for every fMRI study, so researchers only need to apply the relevant methods to their anatomical images to examine cortical and subcortical regions (Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017; Pliatsikas et al., 2014). For example, it is possible that the acquisition of morphology, in either a native or a non-native language, might not only result in local restructuring of the regions that are known to be involved in morphological processing (mostly frontal and subcortical regions and the cerebellum, see above), but also the structural connectivity between these regions, for example as expressed by the increased myelination of the connecting white matter tracts. The relationship between the white matter structure of the brain and morphological processing has only very recently received attention (Yablonski, Rastle, Taylor, & Ben-Shachar, 2018); it is worth noting here that studying the white matter usually requires the acquisition of specialized scans and the use of different analytical methods than those for grey matter.

3. Derivational morphology

Derivational morphology concerns the way new lexical representations are created by combining a base (namely, the root or stem) with one or more affixes (e.g., prefixes, suffixes, infixes) to create polymorphemic words (for reviews, see Aronoff & Fudeman, 2010; Lieber, 2016; Milin, Smolka, & Feldman, 2017). But what do *neuroscientific* research and *polymorphemic* words have in common? Leaving aside the debate on whether neurolinguistics can really inform us about the nature of morphological processing, the most salient answer to this question at the surface level would be that they share the presence of several affixes in the adjectives of the noun phrases: *neuro-* + *science* + *-ic* and *poly-* + *morpheme* + *-ic*. We may not fully understand yet how polymorphemic words are represented, decomposed and processed in the brain, but without exception we would all agree that such words have lexical representations that include at least two morphemes (and hence the *poly-*). And how do we know that on the basis of a unique lexical representation like "polymorphemic"? That is precisely the focus of the current section in which neuroscientific studies on derivational morphology will be reviewed and discussed in an attempt to comprehensively summarize how, when and where in the brain derived words are decomposed and their morphological constituents processed.

In this line, a critical question in the field has been the specific lexico-semantic status held by different types of morphemic representations and the way they parse to create the emerging property of the combinatorial morphology. The greatest issue that has become the focus of attention and debate for several decades is whether or not individual morphemes that constitute a polymorphemic affixed word (e.g., the stem *dark* and the suffix *ness* in the suffixed word *darkness*) are accessed prior to reaching the meaning of the whole string (namely, the meaning of *darkness*), and if that were the case, the precise stage of the word recognition stream at which access to the stems and affixes may take place.

While at first sight it seems relatively straightforward to realize that an English suffix like *-ness* is not a free-standing morpheme that could act nearly as a lexical item, it is also commonly accepted that this bound morpheme typically attaches to participles and adjectives, consistently creating abstract nouns denoting quality, condition or state like in *darkness* (see Medeiros & Duñabeitia, 2016). In fact, and in line with the seminal ideas on affix stripping proposed by Taft and Forster (1975), nowadays most researchers would agree that the processing of a word like *darkness* would be mediated by, or at least implies, a mandatory decomposition into the constituent morphemes by stripping the suffix *ness* from the stem *dark*. However, the affix stripping is a rule of thumb that does not apply equally to all circumstances. For example, consider the obvious differences between the saliency of a free-standing stem like "dark" stripped from "darkness", and of other bound stem morphemes with no lexical entries matching exactly the result of the dissection deriving from the morphological parsing (e.g., *wae* from *waeness*, which is a form of the word *woeness*), or even of pseudo-stems that do not pair with any close representation and which call into question the morphological status of the elements (e.g., *wit* from *witness*). Thus, while there is little debate on that the morphological units of derived words are accessed during word processing, the discussion focuses on the specific moment in which each of the units is accessed and processed, and the way this speaks for individual differences in the concrete properties of the polymorphemic words and of the readers of listeners that process them. Different units may be readily available for processing and segmentation at different stages of the recognition process, and different properties of the bound and free-standing morphemes (e.g., Forster & Azuma, 2000; Moscoso del Prado Martín, Kostic, & Baayen, 2004; Pastizzo & Feldman, 2004), as well as individual differences in the persons processing these units (e.g., Andrews & Lo, 2013; Duñabeitia, Perea, & Carreiras, 2014; Medeiros & Duñabeitia, 2016) have been shown to modulate morphological decomposition mechanisms (see Amenta & Crepaldi, 2012, for review).

As mentioned, the last decade has witnessed an increasing body of evidence showing somewhat conflicting results with markedly different theoretical implications on the extent to what morphological decomposition of derived words takes place at early or late stages of word recognition, mainly linked to either orthographic or semantic processes (see Beyersmann et al., 2016, for a comprehensive review). Given the bulk of evidence showing that non-existing seemingly polymorphemic representations lacking a lexical status (e.g., pseudowords like *quickify*) are, in fact, decomposed into the constituent pseudo-morphemic units (e.g., Beyersmann, Duñabeitia, Carreiras, Coltheart, & Castles, 2013; Longtin & Meunier, 2005; Meunier & Longtin, 2007; Smolka, Zwitserlood, & Rösler, 2007), it seems reasonable to assume that morphological decomposition of derived words is not a process that exclusively occurs post-lexically at a semantic level as initially proposed (see Giraudo & Grainger, 2001). In contrast, the debate has moved now to the time course of morphological decomposition and processing. One of the most relevant current issues concerns the real nature of morphological units like derivational affixes, being them the byproduct of statistically recursive orthographic chunks (the so-called morpho-orthographic views; e.g., Rastle, Davis, & New, 2004), the result of a semantic analysis of the input influencing already the earliest processing stages (the morpho-semantic views; e.g., Feldman, O'Connor, & Martín, 2009), or whether morphological units arise in the interface between orthography and semantics (e.g., Baayen, Milin, Durdevic, Hendrix, & Marelli, 2011; Gonnerman, Seidenberg & Anderson, 2007), and thus their processing will dynamically adhere to both morpho-orthographic and morpho-semantic routes (see Diependaele, Dunabeitia, Morris, & Keuleers, 2011; Diependaele, Sandra, & Grainger, 2005; Duñabeitia, Dimitropoulou, Morris, & Diependaele, 2013).

The aim of the following paragraphs is to offer a snapshot of how cognitive neuroscientists have tried to respond to the abovementioned questions using a variety of presentation modalities (e.g., visual, auditory or multimodal) and research paradigms (e.g., masked and unmasked priming, single word presentation). To this end, the review of the literature will be organized paying special attention to two sources of information that can shed light on the ongoing debates: 1) the time course of morphological decomposition processes of derived words, and 2) the brain networks and areas responsible for the processing of polymorphemic derived words.

3.1. EEG

Most EEG-studies on derivational processes have been conducted in Indo-European languages, such as English, German, French, and Spanish, as well as in Finnish from the Uralic language family. The paradigms include violations of derivational rules, passive-listening oddball, sentence reading, and the majority are priming studies (masked or overt with long visual or auditory prime presentations); the tasks involve (silent) reading, lexical decisions, or semantic decisions. The EEG studies on derivational processing discussed here are summarized in Table 4.

3.1.1. *Violations*

A significant number of studies applied violations to study the morphosyntactic processing of derivations. For example, Bölte, Jansma, Zilverstand, and Zwitserlood (2009) applied violations to German adjective derivations, presented in sentence context. They compared the processing of correct adjectives (e.g., *freundlich*, 'friendly') with two types of violations: possible but nonexisting adjectives (e.g., **freundhaft*, '*friendful'), and anomalous adjectives (e.g., **freundbar*, '*friendive'). Both types of violations induced LAN effects relative to correct derivations, with no difference between them. These findings were interpreted as evidence for morphological decomposition and for a separate handling of structural and semantic information. Also, Leinonen, Brattico, Järvenpää, and Krause (2008) presented violated derivations in sentence context. Relative to the correct derivations (noun stem + suffix), the violated derivations (verb stem + suffix) elicited N400 effects. The authors interpreted these findings as reflecting the parsing of the morpheme combination or as the unsuccessful (or laborious) semantic integration of the morphemic constituents (see also Janssen, Wiese, & Schlesewsky, 2006 for similar N400 findings and violation types in single word context).

Turning to single word studies, in Leminen, Leminen, and Krause (2010) participants made auditory lexical decisions to existing derivations and legal novel derivations in Finnish. Both types elicited N400-like negativities that did not differ from each other and were thus interpreted as evidence for the successful parsing of novel derivations. By contrast, illegal derivations (illegal stem–suffix combinations) produced larger N400 effects, suggesting a more laborious parsing and licensing of the morpheme combination. The results suggest parallel morpheme activation and semantic integration of the morpheme combination when a spoken word temporarily unfolds. In a similar vein, McKinnon, Allen, and Osterhout (2003) compared lexical decisions to existing English words with a bound stem (e.g., *submit*), pseudowords with a bound stem (e.g., **promit*), and unstructured pseudowords (e.g., **flermuf*). Relative to unstructured pseudowords, both words and pseudowords containing bound stems elicited similar N400 attenuations. These findings were taken as support for morphological decomposition that extends to nonproductive and semantically impoverished morphemes.

In contrast to the above studies, two studies that applied the passive-listening oddball paradigm provide evidence against obligatory decomposition. In the Finnish study (Leminen et al., 2013), high-frequency real derivations (e.g., *lauluja*, 'singer') induced enhanced MMNs as compared with low-frequency real derivations (e.g., *kostaja*, 'avenger'). Pseudoderivations (e.g. '**rauluja*', non-existing stem + derivational suffix) elicited a smaller MMN than real derivations. Similarly, in the German study (Hanna & Pulvermüller, 2014), existing derived nouns (e.g., *Sicherheit*, 'security') induced enhanced MMN responses as compared with possible but incorrectly derived nouns (e.g., **Sicherkeit*, '*securation'). In both studies, the increased MMN responses were interpreted as "lexical MMNs", which reflect the automatic activation of the memory traces for existing words (as opposed to the non-existing derived forms) and were thus taken to support whole-word retrieval and/or dual-route processing of derivations.

3.1.2. *Priming*

Most ERP studies on morphological processing have applied repetition priming under masked or unmasked stimulus presentation. In the studies considered here, priming is concluded if the negative going ERP amplitude in the latency range of 250 msec (N250) or 400 msec (N400) is attenuated relative to an unrelated baseline condition, that is, to the most pronounced negativity. In other words, priming occurs if the related condition shows a more positive-going amplitude in the N250 or N400 latency range relative to the unrelated condition (for a review, see Kutas & Federmeier, 2011).

The priming studies typically compare a subset of the following conditions: real morphological derivations (e.g., *hunter–hunt*) as compared to pseudoderivations (e.g., *corner-corn*), and relative to form-related words (e.g., *scandal-scan*). Earlier studies included stem homographs (e.g., Spanish *rata-rato*, 'rat'-'time') or identical words (e.g., French *table–table*) as morphological conditions. If not stated otherwise, real morphological derivations usually refer to fully semantically transparent word pairs (e.g., *hunter–hunt*, *government-govern*; French *lavage-laver*, German *mitkommen-kommen*, 'come along'-'come'), but more recent studies further differentiate between semi-transparent word pairs (e.g., *dresser-dress*), and semantically opaque word pairs (e.g., *apartment-apart*; German *umkommen-kommen*, 'perish'-'come'), and compare these with semantically associated word pairs (e.g., *sofa-couch*; French *linge-laver*, German *nahen-kommen*, 'approach'-'come'). Nonword conditions use pseudoderived nonwords (e.g., **cornity-corn*) or form-related nonwords (e.g., **teble-table*) as primes. In the following, all effects are reported relative to the unrelated/baseline condition. Table 4 summarizes the ERP findings of masked and unmasked priming effects.

3.1.3. *Form priming*

Priming between form-related prime-target pairs (e.g., *teble-table*, *scandal-scan*, French *lavande-laver*, German *kämmen-kommen*) has been classically used to study the time course of visual word recognition in the EEG is thus important for the comparison with morphological processing. Form-related prime-target pairs typically induce an attenuation of the N250 (175–300 msec) and may include a reduction in the N400 effect. Form effects emerged as anterior N250 and N400 attenuations relative to the unrelated condition both under masked priming (Morris, Grainger, & Holcomb, 2008, 2013; Holcomb & Grainger, 2006; Lavric, Clapp, & Rastle, 2007; Morris, Porter, Grainger, & Holcomb, 2011) and under overt

Table 4 – Summary of ERP studies on derivations.

Study	_Language_	_Paradigm_	_Type_	_Modality_	_SOA_	_Sample Size_	_Age range/ mean_	_Task_	_Comparison_	_Examples_	_Effect_
Bölte et al., (2009)	German	violation	adjective suffix	visual		15	–/23	sentence reading	correct versus possible versus anomalous adjectives	_freundlich_ versus *_freundhaft_ versus *_freundbar_	LAN
Leinonen et al., (2008)	Finnish	violation	stem-suffix-combination	visual		15	19–64/ median 25	sentence reading	correct versus violated derivations	_talollinen_ versus* _talolliset mies_	N400
Leminen et al., (2010)	Finnish	violation	stem-suffix-combination	auditory		14	18–27/22	word reading	correct versus novel versus illegal	_melonta_ versus _?_ _elvyntä_ versus*_lelunta_	N400: illegal > novel = correct
McKinnon et al., (2003)	English	violation	stem-prefix-combination	visual		36	18–29/–	word reading	correct versus violated versus pseudoword	_submit_ versus*_promit_ versus *_flermuf_	N400: pseudoword > violated = correct
Leminen et al., (2013)	Finnish	oddball	derivations	auditory		15	21–43/29	passive listening	existing high-frequency versus low-frequency versus pseudoderivations	_lauluja_ versus _kostaja_ versus *_rauluja_	MMN: high > low > pseudo
Hanna and Pulvermüller (2014)	German	oddball	noun suffix	auditory		33 (26)	–/–	passive listening	correct versus violated	_Sicherheit_ versus *_Sicherkeit_	MMN: correct > violated
Holcomb and Grainger (2006)	English	priming	immediate	visual	#50#	48	–/21	SC	Identity: unrelated versus related	_mouth-TABLE_ versus _table–TABLE_	N250 & P325 & N400
									Form-related: unrelated versus related	*_moath-TABLE_ versus *_teble-TABLE_	(right anterior) N250 & N400: identity > form
Morris et al., (2007)	English	priming	immediate	visual	#50#	25 (21)	18–22/20	LD	Transparent: unrelated versus related	_shovel-HUNT_ versus _hunter–HUNT_	ant. N250* & N400*: T > P > F**
									Pseudocomplex: unrelated versus related	_actor-CORN_ versus _corner-CORN_	no effect*
									Form-related: unrelated versus related	_package-SCAN_ versus _scandal-SCAN_	no effect*
Morris et al., (2008)	English	priming	immediate	visual	#50#	54 (48)	18–26/21	SC	Transparent: unrelated versus related	_shovel-HUNT_ versus _hunter–HUNT_	N250 (200–300 msec)*: T = P > F
									Pseudocomplex: unrelated versus related	_actor-CORN_ versus _corner-CORN_	N250*
									Form: unrelated versus related	_package-SCAN_ versus _scandal-SCAN_	ant. N250*
					#100#			SC	Transparent: unrelated versus related		N250* & N400*; N400: T = P = F
									Pseudocomplex: unrelated versus related		N250* & N400*
									Form-related: unrelated versus related		N250* & N400*
Lavric et al., (2007)	English	priming	immediate	visual	#42	24 (22)	19–30/22	LD	Transparent: unrelated versus related	_unrelated-HUNT_ versus _hunter–HUNT_	right post. N250 & N400; N400: T = P > F
									Pseudocomplex: unrelated versus related	_unrelated-CORN_ versus _corner-CORN_	ant. N250 & N400

(_continued on next page_)

Table 4 – (continued)

Study	*Language*	*Paradigm*	*Type*	*Modality*	*SOA*	*Sample Size*	*Age range/ mean*	*Task*	*Comparison*	*Examples*	*Effect*
									Form-related: unrelated versus related	*unrelated-BROTH* versus *brothel-BROTH*	left ant. N250 & N400
Morris et al., (2011)	English	priming	immediate	visual	#50	30 (27)	17–26/20	LD	Transparent: unrelated versus related	*painter-VOLT* versus *voltage-VOLT*	N250 & N400: T = P > F
									Pseudocomplex: unrelated versus related	*painter-VOLT* versus **volter-VOLT*	N250 & N400
									Form-related: unrelated versus related	*painter-VOLT* versus **voltire-VOLT*	N250 & N400
Morris et al., (2013)	English	priming	immediate	visual	#50	27 (24)	18–22/19	SC	Transparent: unrelated versus related	**lendity-HUNTER* versus **huntity-HUNTER*	P (150–200 msec) & N25 & N400:
									Pseudocomplex: unrelated versus related	**towity-CORNER* versus **cornity-CORNER*	N250 & N400
									Form-related: unrelated versus related	**wallity-SCANDAL* versus **scanity-SCANDAL*	N250 & N400: T = P = F
Lavric et al., (2011)	English	priming	immediate	visual	226	14	18–29/22	LD	Transparent: unrelated versus related	*unrelated-HUNT* versus *hunter–HUNT*	N400: T > P > F
									Pseudocomplex: unrelated versus related	*unrelated-CORN* versus *corner-CORN*	N400
									Form-related: unrelated versus related	*unrelated-BROTH* versus *brothel-BROTH*	N400
Barber et al., (2002)	Spanish	priming	immediate	visual	250	10	19–21/–	LD	Inflection: unrelated versus related	*cera-LOCO* versus *loca-LOCO*	N400: Inflection > SHG
									SHG: unrelated vs related	*pera-RATO* versus *rata-RATO*	N400; late N
Dominguez et al. (2004)	Spanish	priming	immediate	visual	300			LD	Inflection: unrelated versus related	*suma-PELO* versus *bobo-BOBA*	P (250–350 msec): Inflection = SHG & N400: Inflection > SHG
						11	18–26/21		SHG: unrelated versus related	*suma-PELO* versus *rata-RATO*	P (250–350 msec) & N400 & late N
						10	19–33/21		Form-related: unrelated versus related	*suma-PELO* versus *toro-TONO*	no effect
						11	20–28/21		Synonyms: unrelated versus related	*suma-PELO* versus *caldo-SOPA*	P (250–350 msec) & N400
Smolka et al., (2015)	German	priming	immediate	visual	300	18 (17)	21–34/–	LD	Transparent: unrelated versus related	*TARNEN-ziehen* versus *ZUZIEHEN-ziehen*	N250 & P325 & N400
									Opaque: unrelated versus related	*TARNEN-ziehen* versus *ERZIEHEN-ziehen*	N250 & P325 & N400: T = O
									Form-related: unrelated versus related	TARNEN-ziehen versus ZIELEN-ziehen	(early) ant. P & N250 & N400

									Semantic: unrelated versus related	TARNEN-ziehen versus ZERREN-ziehen	N400: T = O > S
									O versus F	*ERZIEHEN-ziehen* versus *ZIELEN-ziehen*	N400: O > F
Kielar and Joanisse (2011)	English	priming	immediate	cross-modal	500	16	17-32/24	LD	Transparent unrelated versus related	*illness-HUNT* versus *hunter–HUNT*	N400: T > Semi-t > P/O
									Semi-transparent: unrelated versus related	*dresser-CARE* versus *careful-CARE*	N400
									†Pseudo/Opaque: unrelated versus related	*message-CORN* versus *corner- CORN*	no effect
									Form-related: unrelated versus related	*dragon-PLAN* versus *planet-PLAN*	no effect
									Semantic: unrelated versus related	*doctor-BOX* versus *carton-BOX*	no effect

Notes. LD = lexical decision, SC = semantic categorizations; # = forward or backward mask; SOA = stimulus onset asynchrony; Priming Conditions: I = identity, T = semantically transparent, Ts = semi-transparent, Pseudocomplex = pseudo-morphemic, O = semantically opaque, SHG = stem homograph, F = form-related, S = semantically related, U = unrelated, † 31/47 prime-target pairs were real morphological derivations but semantically opaque of the type *apartment-apart*, 16/47 were pseudocomplex of the *corner-corn* type; primes are presented first, targets second, in UPPER or lower case letters as in the corresponding study.

ERP Effects: N = negativity, *P* = positivity, ant. = anterior, post. = posterior, = or ≠ indicates similar or different effects or > the size of the priming effect (i.e. with a more positive-going attenuation), *when corrected for removed items or multiple comparisons, ** = nonsignificant effects with significant linear trend between conditions; more positive-going deflections of related conditions relative to more negative-going unrelated conditions are interpreted as N250, if they occur within a negativity in the 200–300 msec post-target window, otherwise we refer to them as “early positivity”.

visual priming (Lavric, Rastle, & Clapp, 2011; Smolka, Gondan, & Rösler, 2015), though a single masked-priming study also revealed a reversed form-effect, that is, an N400 increase relative to the unrelated condition (Beyersmann, Iakomova, & Ziegler, 2014). The N250 attenuation is typical for form-related relative to unrelated prime-target pairs. The *dual-route model*, for example, assumes two parallel mechanisms—one orthography-based and one semantically based, hence *form-with-meaning* account. Form-priming in terms of the N250 attenuation reflects the mapping of prelexical representations onto whole-word representations (specifically, a feed-forward prelexical morpho-orthographic segmentation that operates independently of lexical status and semantic transparency (see Morris et al., 2011), while later (N400) effects are thought to indicate the mapping of shared representations at the morpho-semantic level (see e.g., Diependaele et al., 2005; Holcomb & Grainger, 2006; Morris et al., 2011; Morris, Grainger, & Holcomb, 2013). By contrast, the *two-stage model* assumes a single mechanism with two-stages, an orthography-based morphological decomposition followed by semantic interpretation, hence also *form-then-meaning* account (e.g., Lavric et al., 2011).

3.1.4. *Morphological priming—masked*

To establish morphological effects, form priming was typically compared with the effects of morphological conditions, which were identical words (e.g., *table–table*) or semantically transparent morphological derivations (e.g., *hunter–hunt*, *government-govern*). Under masked visual priming, morphologically related (semantically transparent or identical) word pairs like *hunter–hunt* or *table–table* induced either an N250 attenuation alone (Morris et al., 2008) or both N250 and N400 attenuations (Beyersmann, Iakimova, Ziegler, & Colé, 2014; Holcomb & Grainger, 2006; Morris, Frank, Grainger, & Holcomb, 2007; Morris et al., 2008, 2011, 2013; Lavric, Clapp, & Rastle, 2007).

By contrast, pseudoderivations of the *corner-corn* type or nonword pairs of the **cornity-corn* type induced more diverse effects, ranging from no effect (Morris et al., 2007) to N250 attenuations (Morris et al., 2008), and to N250 alongside N400 attenuations (see Morris et al., 2008; Morris et al., 2011; Morris et al., 2013; Lavric et al., 2007). The main interest, however, was in the comparison between the priming by morphologically related, pseudo-derived, and form-related word pairs. For example, Morris et al. (2007) observed significantly more priming by morphologically related words than by either pseudo-derived or form-related words in both the N250 and N400 latency range. However, other studies by Morris et al. (2008; 2011; 2013) found no priming differences between these three types of complexity. Other studies, yet, revealed processing patterns that differed in the early (N250) and the later (N400) effects. Similar N250 deflections by morphologically related and pseudo-derived word pairs were taken as evidence that all words undergo the same segmentation process in early visual word recognition. Similar N400 attenuations by morphologically related and pseudo-derived word pairs were interpreted to indicate a single mechanism with two-stages of form-then-meaning processing: orthography-based morphological decomposition followed by semantic interpretation (see Lavric et al., 2011; Meunier & Longtin, 2007;

Morris et al., 2011). By contrast, similar N400 effects of pseudo-derived and form-related words (Morris et al., 2008, 2011) were interpreted as evidence for a dual-route model that comprises two mechanisms of decomposition: one orthography-based plus one semantically based, hence form-with-meaning (see e.g., Diependaele et al., 2005; Holcomb & Grainger, 2006; Morris et al., 2013).

To summarize, all models so far assume different processing outcomes for semantically transparent and opaque words at the lexical level, when semantic information is integrated (in the two-stage model (e.g., Lavric et al., 2011), or when shared representations operate at the morpho-semantic level (in the dual-route model, e.g., Morris et al., 2013), or when form and meaning codes overlap (in the connectionist model, e.g. Jared, Jouravlev, & Joanisse, 2017). The following paragraphs will review ERP studies that examined lexical representation and processing.

3.1.5. *Morphological priming—unmasked*

Under overt priming conditions with either auditory or visual prime presentations at long SOAs (up to 300 msec), the primes are consciously processed and the meaning of complex words is semantically integrated. Semantic integration and expectation are typically observed in N400 modulations. Indeed, the findings are very clear with respect to morphologically related word pairs like *hunter—hunt*, for which all studies found N400 attenuations (e.g., Dominguez, de Vega, & Barber, 2004; Kielar & Joanisse, 2011; Lavric et al., 2011; Smolka et al., 2015), once preceded by an N250 and P325 modulation (Smolka et al., 2015). Similarly, also inflected word pairs like *loca-loco* ('crazy woman'-'crazy man') revealed N400 attenuations (Barber, Domınguez, & de Vega, 2002), sometimes combined with an earlier positivity (250—350 msec) (Dominguez et al., 2004). By contrast, pseudo-derived words like *corner-corn* or stem homographs like *rata-rato* ('rat'-'time') yield a rather diverse picture, ranging from no effect at all for pseudoderivations (Kielar & Joanisse, 2011), to an early positivity (250—350 msec) for stem homographs (Dominguez et al., 2004), to N400 attenuations for pseudoderivations or stem homographs (e.g., Barber et al., 2002; Dominguez et al., 2004; Lavric et al., 2011), followed by an additional modulation of a late negativity for stem homographs (e.g., Barber et al., 2002; Dominguez et al., 2004. In contrast to the pseudoderivations, purely form-related words usually revealed no substantial effects relative to the unrelated condition (e.g., Dominguez et al., 2004; Kielar & Joanisse, 2011), though an N250 (Smolka et al., 2015) and a (frontal) N400 attenuation were found as well (Lavric et al., 2011; Smolka et al., 2015).

The main interest of the above studies was to investigate the processing of different levels of word complexity. For example, Lavric et al. (2011) found that the N400 effect was largest when it was induced by morphologically related word pairs like *hunter—hunt*, smaller by pseudoderivations like *corner-corn* and smallest by purely form-related words like *brothel-broth*. Because morphologically related and pseudo-derived word pairs showed similar effects during an early N400 time window and differed in a later N400 time window, these differences in N400 attenuations were interpreted in favor of a two-stage (i.e. form-then-meaning) model of visual word recognition, with orthography-based morphological decomposition in the first stage, and validation by semantic information at a later stage.

By contrast, Kielar and Joanisse (2011) found evidence in favor of the *convergence-of-codes* view. Specifically, they manipulated the semantic transparency of real morphological derivations between fully transparent (*government-govern*), semi-transparent (*dresser-dress*), and semantically opaque (2/3 real morphological derivations like *apartment-apart*; 1/3 pseudoderivations like *corner-corn*). They found similar N400 priming effects for semantically transparent and semi-transparent and no effect at all for semantically opaque pairs. In line with the distributed-connectionist or convergence-of-codes view, "morphological effects were graded in nature and modulated by phonological and semantic factors" (Kielar & Joanisse, 2011, p. 170). Because neither pure form similarity like *panel-pan* nor semantic associations like *sofa-coach* produced any significant effects, the authors concluded that the morphological effects could not be explained by pure form or meaning relatedness alone.

In contrast to the above studies in English, an ERP study on German complex verbs found morphological effects that were unaffected by form or semantic factors (Smolka et al., 2015). They manipulated the semantic transparency of real morphological derivations between fully transparent (e.g., *mitkommen-kommen*, 'come along'-'come') and semantically opaque (e.g., *umkommen-kommen*, 'perish'-'come'), and found equivalent N250, P325, and N400 priming effects for semantically transparent and opaque derivations. Furthermore, the morphological N400 attenuations were stronger than those elicited by semantic associates (e.g., *nahen-kommen*, 'approach'-'come'); and the morphological effects clearly differed from the early right frontal positivity that converged into an N250 effect and further extends to a frontal N400 effect by purely form-related pairs (e.g., *kämmen-kommen*, 'comb'-'come'). The German findings clearly deviate from findings in English where morphologically related but semantically opaque derivations did not induce any priming effect in this condition (Kielar & Joanisse, 2011). These findings were taken to indicate stem access in German regardless of the semantic transparency of the whole word.

Finally, when morphological effects were compared to semantic effects, one study observed no effect for semantic associations (Kielar & Joanisse, 2011), while two studies found N400 modulations for synonyms (Dominguez et al., 2004) or semantically associated verbs (Smolka et al., 2015), indicating that semantic associations are automatically activated within the semantic network.

3.2. *MEG*

While MEG studies on inflected words are, in general, in line with the account that the processing of inflection involves combinatorial processing, the studies on derivations offer a more discrepant range of findings, particularly with respect of timing of morphological parsing. Table 5 demonstrates the MEG studies on derivation. The varying MEG results are mostly interpreted to be in line with either full decomposition accounts and/or dual route accounts. As with inflections, the majority of MEG studies on derivations have attempted to find neural support for the behavioral evidence of early obligatory decomposition of complex words—will decomposition be witnessed at the very early stage of processing (M170) or does semantic still play a role (M350/N400 m)? The large part of the studies has been conducted using English stimuli, with only a few exceptions (see Table 5).

To begin with *unprimed lexical decision tasks*, Zweig and Pylkkänen (2009) reported a larger right-hemisphere dominant M170 response for the processing of derived (*farmer*, *refill*) words as opposed to simplex (*switch*) and control (*winter*, *recon*) words, interpreted to reflect an early prelexical processing stage. Recall from the section on MEG studies of inflection that the M170 effect has been attributed to the early morphological parsing processes. The M170 results were clearer for the transparent but not for the opaque words, and it was concluded that "the M170 decomposition effect extends to opaque words in some partial way underdetermined by (our) current analysis methods" (p. 426). Curiously, there were no behavioral effects of morphological complexity, and the interpretation was that morphological complexity is not associated with a processing cost that is directly reflected in lexical decision times. Solomyak and Marantz (2010) went further to study derived words containing free stems (*taxable*), bound roots (*tolerable*) and unique roots (*vulnerable*). While there were no reaction time (RT) differences between the derived words and monomorphemic controls, Solomyak & Marantz reported reliable M170 effects for the free and bound root, suggesting early morphological decomposition (for the M170 findings with pseudoaffixed words, see Lewis, Solomyak, & Marantz, 2011). In addition, there was a significant effect of lemma frequency in the M350 time-window, interpreted as reflecting successful parsing. Solomyak & Marantz also showed an effect of transitional probability on the M170. However, the results on the unique roots were inconclusive and the question whether they are decomposed or not was left open. More recently, Fruchter and Marantz (2015) showed an effect of derivational family entropy[3] in left temporal neural regions from 240 msec onwards, reflecting decomposition into stems and affixes, and an effect of surface frequency in the left temporal area within a time-range of 430–500 msec, reflecting the later recombination stage. Fruchter and Marantz (2015) also introduced the concept of semantic coherence, a statistical measure used to quantify the gradient semantic well-formedness of complex words, which elicited an effect in left orbitofrontal cortex in the 350–500 msec time window.

Priming studies have shown both prelexical and lexical effects for derived words, again suggesting support for morphological decomposition. Using masked priming, Lehtonen, Monahan, and Poeppel (2011) reported the left occipito-temporal response taking place ~220 msec, resembling the M170 by its magnetic field distribution. This response was sensitive to morphological prime–target relationship and was not modulated by semantic transparency between the prime and target, suggested to reflect a prelexical level of processing. Interestingly, however, opaque words with high transitional probability[4] did not show significant priming effects in either behavioral or MEG responses. This result was tentatively interpreted as suggesting that at least those semantically opaque words that are relatively high-frequent forms in the family of their stems, may not be decomposed early, which supports dual-route accounts. In an extensive region-of-interest analysis, Cavalli et al. (2016) contrasted morphological, unrelated, orthographic, and semantic priming effects in a visual priming paradigm (the target was presented 50 msec after the prime). Morphological priming effects were observed in the middle left inferior and anterior temporal ROIs (M350 msec time-window), in the left superior temporal ROI (in the time window of the M250 later, at 585–650 msec), in the left inferior temporal ROI (the 345–420 msec and 440–495 msec time-windows), as well as left orbitofrontal ROI (the M350 time-window). There were no significant morphological priming effects prior to the M250 time-window. Cavalli et al. introduced a detailed spatiotemporal model, in which the morphological structure is analyzed with respect to the semantic overlap in the left superior temporal gyrus (LSTG) at 250 msec after the stimulus onset. Thereafter, the activation would be passed on to LIFG if a morphologically complex prime shared meaning with the target. Form primes might be recognized as orthographic competitors and would be inhibited in LSTG. Lexical access of morphemes might occur in the 350 msec time-window in the middle and anterior left inferior temporal gyrus (LITG). The activation then proceeds onto left inferior and orbitofrontal areas, where morphemes are recombined to recognize the whole word.

Whiting, Shtyrov, and Marslen-Wilson (2015) contrasted simple (*walk*), complex (*farmer*), and pseudocomplex (*corner*) words in an occasional recognition task. Morphological effects emerged at approximately 300–370 msec from stimulus onset, where complex stimulus sets diverged from the noncomplex stimulus sets. More specifically, derivations diverged from the noncomplex stimuli in left middle temporal gyrus (MTG) at around 330 msec, but complex versus pseudocomplex words did not differ. Whiting et al. also found differences between inflected and noncomplex stimuli 300–370 msec in left posterior MTG and LIFG, but with no differences between real and pseudoinflections. The results were interpreted as being in line with behavioral masked priming evidence, suggesting that morphological structure analysis triggers lexical access in left middle temporal regions from 300 msec onwards and is not initially constrained by lexical-level variables. Furthermore, Bölte, Schulz, and Dobel (2010) approached derivational processing using an unprimed synonym judgment task. They compared reading of existing derived German adjectives (*freundlich*, 'friendly'), non-existing, but semantically legal (synonymous) adjectives (**freundhaft*), and non-existing, semantically and morphologically illegal adjectives (**freundbar*). The processing of derivations elicited a gradual increase of activity in the left temporal lobe in the N400m time-window, i.e., activity increased from existing over legal to illegal adjectives. The gradual increase of the N400m was taken to reflect either the semantic interpretation or the morphological integration of decomposed constituents (for similar interpretation of the EEG findings, see e.g., Leminen et al., 2010 described above).

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[3] A statistical measure derived from the lexical frequencies of the morphological family members of a stem (Fruchter & Marantz, 2015).

[4] The probability of encountering a particular suffix after a given stem.

Table 5 – ***Summary of MEG studies on derivations. The studies used single word tasks.***

Study	Language	Task	Modality	Sample size	Age range/ mean age	Grammatical category	Comparison	Time-course of morphological effects and their neural sources
Whiting et al., 2013	English	Passive listening	Auditory	15	19–34	Noun	Transparent and opaque derivations	MMN, post-MMN, left fronto-temporal areas
Leminen et al., 2011	Finnish	Acceptability judgment	Auditory	10	18–34	Noun	Derivations > Monomorphemic Derivations > Inflected	Superior temporal area
Leminen et al., 2013	Finnish	Passive listening	Auditory	10	18–34	Noun	Derivations > Monomorphemic Derivations > Inflected	Early automatic response, STG
Cavalli et al., 2016	French	Lexical decision (priming)	Visual	20	23.4	Nouns	Morphologically related > Semantically related > Orthographically related	LH inferior temporal gyrus (M350), superior temporal gyrus (M250 and ~ 585 −650 msec) msec), inferior frontal gyrus (345–420 msec and 440–495 msec), orbitofrontal gyrus (435–500 msec)
Fruchter & Marantz, 2015	English	Lexical decision	Visual	12	19–32	Nouns	Modulation of surface frequency and derivational family entropy, Semantic coherence	Left middle temporal, left middle-anterior fusiform, inflerior temporal ROIs
Lehtonen et al., 2011	English	Lexical decision (masked priming)	Visual	16	22.6	Nouns	Semantically transparent > opaque pairs < unrelated	M170, Left occipito-temporal cortex
Bölte et al., 2010	German	Synonym judgment	Visual	16	28	Nouns	Correctly derived pseudowords > Incorrectly derived pseudowords > Existing derivations	N400, left superior temporal cortex
Zweig & Pylkkänen, 2009	English	Lexical decision	Visual	16	20–32	Nouns	Transparent derivations > Opaque derivations > Simple words	M170, Left temporo-occipital area
Solomyak & Marantz, 2010	English	Lexical Decision	Visual	9	19–29	Adjectives	Bound roots > Unique roots > Free stems	M170, M350, Posterior occipital area, Occipito-temporal fusiform gyrus, Left superior temporal, Sylvian fissure regions
Whiting et al., 2015	English	Occasional recognition task	Visual	16	18–35	Nouns	Simple > Complex > Pseudocomplex > Noncomplex	300–370 msec, left MTG (derivations), LIFG, left posterior MTG (inflections)

Scarce MEG studies on *auditory* processing with active and passive listening also speak for decompositional and/or dual-route processing of derivations. For instance, Whiting et al. (2013) reported increased left-lateralization for semantically transparent and opaque forms (*baker* and *beaker*), taken to suggest that morphological processing is elicited by any form containing morphological structure, regardless of word meaning. In addition, the semantically opaque word (*beaker*) elicited larger activation than the transparent one (*baker*) ~240 msec after the divergence point in the left middle temporal cortex, interpreted to signal re-analysis processes since a decompositional meaning is not appropriate. In two studies, Leminen and colleagues (Leminen et al., 2011, 2013) did not observe differences between simple and derived words at later stages of processing (~200 msec onwards), which was interpreted to support dual-route accounts of morphological processing. However, derivations elicited an increased early (80–120 msec) MEG response in the temporal area, which was not modulated by attention (Leminen et al., 2013), taken to suggest early automatic suffix-related activation and/or activation of a full-form representation for derived words.

3.3. fMRI

A substantial number of fMRI studies have looked at the processing of derivation by investigating which parts of the brain are activated for morphologically complex words. Much of this literature has been concerned with issues such as whether derivation is a grammatical operation which, similar to inflection, can be localized in the brain and produce effects that are distinct from orthographical or phonological processing, whether derivations really are morphologically complex or they are processed as whole words in the brain, and, if they are complex forms, which are the grammatical constraints that mediate their processing. The available studies to date are illustrated in Table 6. Similar to inflection, most of these studies have been conducted in English, and have mostly looked at the processing of derived nouns, with some studies including adjectives and verbs.

The early studies in the field were heavily influenced by behavioral literature suggesting that word processing is mediated by orthography, phonology and/or semantics, and that especially derivation can be reduced to a combined operation of orthography and semantics, without necessarily having a grammatical reality itself (Marslen-Wilson, Tyler, Waksler, & Older, 1994; Rastle et al., 2004). Indeed, the first published fMRI study suggested that derivations do not differ from simple words with respect to patterns of brain activation they elicit (Davis et al., 2004). A few of the earlier fMRI studies used masked priming, a method that has been widely used to unveil morphological and orthographic relationships between pairs of words (Grainger, Colé, & Segui, 1991); for example, Devlin, Jamison, Matthews, and Gonnerman (2004) revealed that, compared to unrelated word pairs (*award-munch*), derivational pairs (*hunter–hunt*) activated temporal and parietal regions that were not uniquely activated by those items, but were also activated for word pairs with orthographic (*passive-pass*) and semantic (*sofa-couch*) relationship, suggesting that morphology is not an independent operation but emerges from the convergence of form and meaning. In another masked priming experiment, Gold and Rastle (2007) reported reduction in brain activity of occipital regions for word pairs containing pseudo-derivations with components that could function as valid morphemes (*archer-arch*) and for pairs with orthographic overlap (*pulpit-pulp*) compared to controls, further suggesting that derivational processing is heavily, if not exclusively, mediated by orthography. The issue has been examined with a variety of tasks beyond masked priming, including auditory tasks, and it remains controversial, at least with respect to English derivation, with evidence suggesting both that derivations are processed via decomposition (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007), which is generally expressed as increased activity in the LIFG, and that they are processed as whole words (Bozic, Tyler, Su, Wingfield, & Marslen-Wilson, 2013), expressed as activity in a widespread bilateral frontotemporal network. It has also been argued that processing of derivations might be mediated by their lexical properties. For example, Vannest, Polk, and Lewis (2005) reported increased activation in Broca's area and the basal ganglia for derivations that include highly productive suffixes (e.g. *-ness*) compared to less productive ones (e.g. *-ity*), indicating morphological decomposition for the former and whole-word processing for the latter. However, it was later argued these effects are modulated by the frequency of the base form of the derivation (Vannest, Newport, Newman, & Bavelier, 2011; see also; Blumenthal-Dramé et al., 2017). Nevertheless, and moving away from English derivation, masked priming studies in Hebrew have shown reductions in brain activity in bilateral frontal, temporal and parietal regions for morphologically related pairs, compared to orthographic or semantic pairs, providing evidence for morphological processing that is independent from form and meaning, at least in Hebrew (Bick, Frost, & Goelman, 2010; Bick, Goelman, & Frost, 2011; see also Bick, Goelman, & Frost, 2008 for more similar evidence in Hebrew with a different task).

The relatively robust effects reported in Hebrew, and the less clear picture for English, strongly suggest that the processing strategies of decomposition might be language-specific, but the field is still quite small to ascertain this. Nevertheless, some patterns do seem to emerge: for example, the two available studies in Italian (Carota, Bozic, & Marslen-Wilson, 2016; Marangolo et al., 2006) strongly argue for processing of derivations as decomposable forms; similar arguments have also been made for derivation in Dutch (De Grauwe, Lemhöfer, Willems, & Schriefers, 2014), but not in Slavic languages like Polish (Bozic, Szlachta, & Marslen-Wilson, 2013) and Russian (Klimovich-Gray et al., 2017), where the available evidence indicates whole-word processing of derivations. It is worth pointing out that the available evidence is based on a variety of different tasks which have been variably used in different languages. However, there seems to be a small chance that the reported contradictory patterns are due to task effects, since tasks like masked priming or *n*-back have produced different results in different languages (see Table 6). Conversely, a likely explanation for these language-specific effects might be related to different lexical properties between languages, including semantic relatedness, suffix productivity and lexical competition between related forms, which might differentially affect the neural representation of derivations in different languages. For example, Carota et al. (2016) demonstrated that, while transparent Italian derivations with productive affixes show neural activity clearly consistent with decomposition, and opaque derivations with nonproductive suffixes are processed as whole forms, processing of other types, (e.g. opaque derivations with otherwise productive affixes) heavily depends on the degree of the productivity of the affix, as well as the semantic relatedness between the derived and the base form. Importantly, these parameters have been shown to modulate the level of activation of the fronto-temporal regions that are typically involved in whole-word processing. This explanation (which is also compatible with the evidence from Vannest et al., 2011, and Marangolo et al., 2006) has been used to account for the variability among different results in different languages, with Carota and colleagues suggesting that semantic relatedness is crucial for derivational processing in languages like English, Polish and Italian, but not for Arabic. It is also worth mentioning here that some of the more nuanced evidence in the field comes from a cohort of studies that have moved away from classic univariate fMRI analyses and have employed multivariate approaches (e.g. Bozic et al., 2015; Carota et al., 2016; Klimovich-Gray et al., 2017), suggesting that such approaches might be more sensitive to the neural computations related to different types of morphology.

It is worth noting that hardly any evidence has been provided for types of derivation that require more than a stem + suffix concatenation. Only a handful of studies have looked at more complex derivations, by investigating the linguistic rules and constraints that dictate their formation, as well as their brain correlates. Specifically, Meinzer, Lahiri, Flaisch, Hannemann, and Eulitz (2009) look at processing of German complex derivations by comparing 1-step derivations, i.e. those requiring a single conversion, e.g. from adjective to noun (*müde* - > *Müdigkeit* 'fatigue') to 2-step derivations, which entail an intermediate derivational step, e.g. from verb to adjective to noun (*lesen* - > *lesbar* - > *Lesbarkeit* 'legibility'), meaning that their derived forms differed in *derivational depth* but not in terms of their surface properties (i.e. they had the same suffix and comparable length). They revealed that derivational depth modulated the level of activation in several brain areas, and particularly left frontal, temporal and parietal regions. This suggested that derivational processing entails more than just affix-stripping and it requires processing of the full derivational route down to the base form. This finding was further corroborated by a subsequent study by Pliatsikas, Wheeldon, Lahiri, and Hansen (2014) who reported comparable effects of derivational depth in English; notably in that study 2-step derivations included an intermediate step that was not marked orthographically or phonologically (*zero derivation*, e.g. $boat_{\mathrm{NOUN}}$ - > $boat_{\mathrm{VERB}}$ - > $boating_{\mathrm{NOUN}}$), and were compared to 1-step derivations that had identical structure (stem + suffix) but were derivationally more "shallow" (e.g. run_{VERB} - > $running_{\mathrm{NOUN}}$). In other words, it was suggested that processing of the full derivational route also applies to complex derivations with intermediate steps that are not orthographically or phonologically realized, contrasting earlier suggestions that derivation emerges simply through the combination of form and meaning.

The available evidence clearly illustrates that the debate about the nature of derivational processing is far from over. However, the Meinzer et al. (2009) and Pliatsikas et al. (2014) studies indicate that, in order to understand derivation better, future fMRI studies should expand their remit to different types of derivation, including prefixation (e.g. *re-play*) and multiple affixation (e.g. *un-happy-ness*), which are currently absent from the literature.

4. The morphology of compounding

Most languages use compounding as the main morphological operation to create new lexical items (see Pollatsek, Bertram, & Hyönä, 2011). Given the huge number of novel compounds that can be created by concatenating different word types, compound words have been considered as the morphological foundation of lexical productivity (cf. Libben, 2014). In contrast to other rule-based operations that follow relatively strict parsing criteria (like the grammatical operations yielding inflectional morphology, or the precise position within the strings of certain types of derivational affixes), compounding is governed by more malleable principles. Take, for instance, the word *man*. By simply concatenating the derivational affix *-ly* one can get the derived word *manly*. But the properties and rules of derivational operations and of the specific morphemes state that *-ly* cannot be used as a prefix, given that it is a suffix and its expected position is after, and not before, the base form. However, a markedly different scenario is offered by compound word creation, insofar the lexeme *man* can be freely used in different positions within a compound, being the first constituent lexeme in *manpower*, or the second constituent in *milkman*. This relative freedom in positioning a given constituent morpheme within a compound means that there are different possibilities for compound word construction, and that two or more elements can be differently combined to create a compound. Closed compounds are the prototypical form of lexicalized compounds, and they present a series of constituent morphemes that are concatenated creating a single non-spaced and non-hyphenated lexical representation (e.g., *postman*). But in some other circumstances, compound words are created by separating the constituent morphemes by a hyphen (e.g., *man-made*), or by separating the morphemes by a space (e.g., *straw man*). Thus, compounding offers a large variety of possible operations to create morphologically complex items, and for this reason compound word processing has been in the focus of psycholinguists exploring word creation and decomposition (see Juhasz, 2018, for review).

A great body of studies has focused on the specific properties of the constituent morphemes in closed, or lexicalized, compounds, which modulate lexical access and morphological decomposition (see Juhasz, Lai, & Woodcock, 2015; Kuperman, 2013). In order to study this, most experiments have either manipulated the frequencies of the constituents (e.g., Andrews, Miller, & Rayner, 2004; Bertram & Hyönä, 2003; Pollatsek, Hyönä, & Bertram, 2000), the semantic transparency of the whole compound and of its parts (i.e., opaque *vs.* transparent compounds; e.g., Juhasz, 2007; Marelli & Luzzatti, 2012; see Libben, 1998, for discussion on this matter), or the

Table 6 – Summary of fMRI studies on derivation. All studies used single word tasks. Only findings related to morphological decomposition are reported.

Comprehension tasks

Study	Language	Task	Modality	Sample size	Age range/ mean age	Grammatical category of complex forms	Comparison	Activated brain regions
Devlin et al., 2004	English	masked priming with lexical decision	visual	12	18–25	nouns & adjectives	Morphological < unrelated pairs	BIL: AG L: MTG, OTC
Davis et al., 2004	English	1-back synonym-monitoring task	visual	11	18-40[a]	nouns & adjectives	Derived > simple forms	No effects
Vannest et al., 2005	English	encoding task with recognition test	visual	15	18–25	nouns	“Decomposable” (*happiness*)> “whole-word” (*serenity*) derivations	L: Broca's (broadly defined ROI) BIL: Basal ganglia (single ROI)
Bozic et al., 2007	English	delayed repetition priming	visual	15	Not reported	nouns/ adjectives/ adverbs	First presentation: opaque and transparent derivations > simple forms Second presentation (priming effect) opaque and transparent derivations < simple forms	L: IFG L: IFG, INS
Gold & Rastle, 2007	English	masked priming with lexical decision	visual	16	M = 23.6, SD = 4.1	nouns/adjectives	Morphological < unrelated pairs Morphological + Orthographic < unrelated pairs Semantic < unrelated pairs	L: MOG L: MOG, FFG L: MTG
Bick et al., 2008	Hebrew	morphological/ semantic/ orthographic/ phonological similarity judgment on word pairs	visual	14	20–50	nouns	Morphologically related pairs > visual controls Morphologically related pairs > semantically + orthographically + phonologically related pairs	L: IFG, MFG, CN, PCG, STS, MTG, IPS, AG, OTS, FFG, LG R: Cuneus L: MFG, IPS, AG R: LG
Meinzer et al., 2009	German	unmasked lexical decision	visual	24	M = 26.1	nouns	Complex nouns > letter strings 2 step derivations> 1 step derivations	BIL: IFG, MFG, cuneus; R: MFG L: PCG, BG, MTG, SPG, IPG. L: IFG, MFG, MTG, STG, MOG, IOG R: STG, MTG, IOG, cuneus, precuneus
Bick et al., 2010	Hebrew	masked priming with lexical decision	visual	20	18–31	nouns/adjectives	Morphologically related pairs < semantically + orthographically + related pairs + control pairs	BIL: IFG, MFG, PCG, IPS, IPL, STG, AG, Cingulate, Precuneus
Bick et al., 2011	Hebrew & English	masked priming with lexical decision	visual	27	22–36	nouns/adjectives	Morphologically related pairs < semantically + orthographically + related pairs (overlapping for both English and Hebrew)	L: IFG, MFG, SMA, visual regions R: IFG, visual regions
Vannest et al., 2011	English	unmasked lexical decision	visual	18	18-30[a]	nouns	“Decomposable” (*happiness*)> “whole-word” (*serenity*) derivations “Decomposable” + “whole-word” derivations > simple words	No differences. Activation in various brain regions modulated by base frequency L: IFG and STG

(*continued on next page*)

Table 6 – (*continued*)

Comprehension tasks

Study	Language	Task	Modality	Sample size	Age range/ mean age	Grammatical category of complex forms	Comparison	Activated brain regions
Bozic, Tyler et al., 2013	English	auditory gap detection	auditory	18	Not reported	nouns/ adjectives/verbs	Opaque > transparent derivations	BIL: MTG; R: IFG
Bozic, Szlachta et al., 2013	Polish	attentive listening paradigm, with an occasional 1-back memory task	auditory	20	18-36[a]	nouns/ adjectives/verbs	Opaque derivations > transparent derivations Opaque derivations > simple words	L: STG, MTG L: STG, MTG
De Grauwe et al., 2014	Dutch (native and nonnative speakers combined)	delayed priming with a go/no go task (respond to non-words only)	visual	39	18–29	verbs	Unprimed > primed Primed > unprimed	L: IFG, INS, SMA, STS; BIL: SFG L: INS, STG; R: STG, HIP, IPL; BIL: CER
Pliatsikas et al., 2014	English	Unmasked lexical decision	visual	21	M = 20.4, SD = 2.96	nouns	Derived > monomorphemic words 2 step zero derivations > 1 step overt derivations	L: IFG, TOC, BIL: OFG L: IFG
Carota et al., 2016	Italian	attentive listening paradigm, with an occasional 1-back memory task	auditory	20	Not reported	nouns	Opaque > transparent derivations Opaque with nonproductive suffixes > with productive suffixes	BIL: STG, MTG, IFG BIL: STG, MTG; R: IFG
Klimovich-Gray et al., 2017	Russian	attentive listening paradigm, with an occasional 1-back memory task	auditory	20	19–39	nouns	Complex derivation > simple derivation	L: STG
Blumenthal-Dramé et al., 2017	English	Masked priming with lexical decision	visual	19	19–61	nouns and adjectives	Correlations between word frequency and BOLD signal for deriv–stem pairs Positive Correlations between word frequency and BOLD signal for stem–deriv pairs Positive Negative	L: PCG, IFG, LG, FFG, IOG R: SMA; BIL: IOG L: Precuneus; R: ACC, AG, SMG L: IFG, SFG, PCG, MFG, TP, THA, GP, FFG, ITG, IPL, SPL, MOG R: INS, claustrum, IFG, MFG, SFG, THA, CN, LG, cuneus,
Production tasks								
Marangolo et al., 2006	Italian	Word generation task	auditory	10	21–29	nouns and verbs	verb-to-noun derivation > repetition adjective-to-noun derivation > repetition noun to-verb derivation > repetition	L: IFG, PCG, INS, IPL, AG, SPL R: IFG, MFG, AG, SPL, CN L: IFG, INS, MFG, IPL, SPL, AG, SMA, MTG, GP R: AG, IPL, CN L:IFG, PCG

[a] Age range for the original sample of these studies. The Ns reported here are after participant exclusions. No age range reported for the samples after the exclusions.

relative contribution of the individual lexemes to the general meaning of the compound (i.e., the compound's headedness; e.g., Inhoff, Starr, Solomon, & Placke, 2008; Marelli, Crepaldi, & Luzzatti, 2009). So far, there is general agreement in that morphological decomposition of compounds is mediated by factors such as the semantic transparency, the frequency of the constituents and the headedness of the compounds, even though the contribution of these factors may depend on the specific task demands (see Juhasz, 2018).

Together with the results from studies exploring the importance of the aforementioned variables, another series of experiments investigating access to the individual lexemes by means of constituent masked and unmasked priming have also demonstrated that compound words are processed via their morphemes (e.g., Crepaldi, Rastle, Davis, & Lupker, 2013; Duñabeitia, Laka, Perea, & Carreiras, 2009). Strong evidence for the morphological decomposition of compound words comes from studies showing that the processing of a compound word like *milkman* can be facilitated by the presentation of one of its constituents prior to it (e.g., *man*; see Duñabeitia, Marín, Avilés, Perea, & Carreiras, 2009; Libben, Gibson, Yoon, & Sandra, 2003; Smolka & Libben, 2017). In the same vein, a compound word like *manpower* facilitates the recognition of a compound like *milkman* via cross-position constituent priming (Duñabeitia et al., 2009), and a pseudocompound like *manmilk* facilitates the access to the real compound word *milkman* too (Crepaldi et al., 2013). Thus, as Libben (2014, p. 11) nicely summarizes, it is broadly accepted that "*the mental representation of compound words requires the equivalent of whole word representation as well as representations of their constituent lexemes*".

As inferred from the title of this manuscript, the neuroimaging literature on compound word processing is not as dense and the results are not as complete as in the cases of inflection or derivation. The readership will easily appreciate from the length and depth of the subsections presented below that the EEG, MEG and fMRI research on compounding is somewhat scarce. The aim of most of these studies is circumscribed to investigating the critical variables mentioned before (i.e., constituent frequency, semantic transparency and headedness) as a tool to uncover the specific stages of compound word processing at which the constituent morphemes are accessed during word recognition and production. While it is clearly evident from the length of the list of studies reviewed below that additional research is needed on this topic, it is worth mentioning that for such a reduced number of articles, marked incongruence can be found across the results presented in these studies, speaking for the need of further research.

4.1. EEG

One of the basic questions behind research on compounds is whether they are processed and represented as unitary lexical units or as combinatorial constituents. Most EEG studies on compound processing have been conducted in Indo-European languages, such as English, German, Dutch, Italian, but a study in Basque (a language isolate) and a study in Chinese are represented here as well. The paradigms include violations (of gender, infixes, or plural), passive-listening oddball, long-lag repetition priming, sentence or single word reading, associative recognition; and the tasks involve word and picture naming, lexical decisions, and grammaticality or familiarity judgments. The EEG studies on compound processing that are discussed here are summarized in Table 7.

4.1.1. *Violations*

Violation paradigms have been used to study the morphosyntactic processing of compounds. For example, Koester and colleagues (Koester, Gunter, & Wagner, 2007; Koester, Gunter, Wagner, & Friederici, 2004) applied gender violations to the first or second constituent of German compounds and manipulated the gender agreement between a determiner and the first constituent or the head of existing 2-word compounds (e.g., *der *Reisfeld*, '*the$_{\text{masc}}$ rice$_{\text{masc}}$ field$_{\text{neuter}}$') or novel three-word compounds (e.g., *das *Sofakissenbezug*, '*the$_{\text{neuter}}$ sofa$_{\text{neuter}}$ pillow$_{\text{neuter}}$ cover$_{\text{masc}}$'). Participants judged the gender agreement of the compound. Although the gender of the first constituent is irrelevant in German, gender-incongruent first constituents induced a LAN effect. This implies that the gender feature of the first constituent was accessed. Furthermore, gender-incongruent heads induced a LAN and a late positivity, independent of the compound's transparency. This was taken to suggest that both transparent and opaque compounds are decomposed, and that both first constituents and heads are accessed morphosyntactically. In a comparison to low-frequency 2-word compounds, transparent compounds showed a slow negative shift (600–1200 msec), which was interpreted to reflect the semantic processing and integration of the constituents. The authors concluded that all compounds, transparent and opaque, are morphologically complex, but only (low-frequent) transparent compounds are semantically complex (for similar behavioral results see Dohmes, Zwitserlood, & Bölte, 2004).

Krott et al. (2006) compared Dutch existing and novel 2-word compounds in the correct plural form (*damessalons*, 'women's hairdresser salons') to violations of the interfix (**damensalons*), violations of the plural (**damessalonnen*), or of both (**damensalonnen*). They observed a widespread N400 effect for novel compounds relative to existing ones. Moreover, existing compounds elicited LAN effects for suffix and interfix violations as well as a posterior positivity (900–1200 msec) for interfix violations, while novel compounds showed a LAN and a posterior positivity for suffix violations. The LAN effects were interpreted to result from the partial mismatch of a morphologically complex form with a stored form (rather than the violation of (morpho) syntactic rules).

4.1.2. *Transposed letters*

Stites, Federmeier, and Christianson (2016) applied transposed letters (TLs) to compounds to study whole-word versus morphological processing. Participants read sentences with correct compounds (e.g., *cupcake*), with compounds with letters transposed within a morpheme (e.g., *cupacke*), and with compounds with letters transposed across morphemes (e.g., *cucpake*). They found that, relative to the correct compound condition, both TL conditions elicited a late posterior positivity (600–900 msec) that did not differ between the two

Table 7 – Summary of ERP studies on compound processing.

Study	Lang	Paradigm	Task	Modality	Sample Size	Age Range/ Mean	Type of Compound	Comparison	Examples	Effect
Koester et al., (2004)	German	gender violation	gender judgment	auditory	23	19–31/25	existing 2-constituent	correct versus violation: first constituent	_der Regentag_ versus *_der Reisfeld_	LAN
								correct versus violation: first constituent	_das Presseamt_ versus *_das Nussbaum_	LAN + late positivity
Koester et al., (2007)	German	gender violation	gender judgment	auditory	30	18–30/24	novel 3-constituent	first constituent: correct versus violation	_der Stahlhakenpreis_ versus *_der Bretterastloch_	LAN
								head constituent correct versus violation	_das Autodachfenster_ versus *_das Bankettmenüteller_	LAN + late positivity
					40	19–30/23	existing 2-constituent	transparent versus opaque	_Nussbaum_ versus _Luftschloss_	late negativity (600–1200 msec)
Krott et al., (2006)	Dutch	interfix + plural violation	silent reading	visual	42 (32)	18–26/22	existing + novel 2-constituent	existing versus novel	_damessalons_ versus _kruidenkelken_	N400
								existing: correct versus incorrect interfix	_damessalons_ versus *_damensalons_	LAN + late positivity
								existing: correct versus incorrect plural	_damessalons_ versus *_damessalonnen_	LAN
								novel: correct versus incorrect plural	_kruidenkelken_ versus *_kruidenkelks_	LAN + late positivity
Kaczer et al., (2015)	Dutch	long-lag repetition priming	word + picture naming	visual	22 (18)	19–25/–	existing + novel 2-constituent	unrelated versus existing versus novel	unrelated-_appel_ versus _appelmoes-appel_ versus _appel gezicht-appel_	N400, marginally larger for novel
Koester and Schiller (2008)	Dutch	long-lag repetition priming	word + picture naming	visual	23 (15)	19–39/25	existing 2-constituent	unrelated versus transparent versus opaque	_gnoom-ekster_ versus _eksternest-ekster_ versus _eksteroog-ekster_	N400, transparent = opaque
Eulitz & Smolka, (2017)	German	single word presentation	lexical decision	visual	25	19–36/–	existing + novel 2-constituent	transparent versus opaque versus novel	_Hundeauge_ versus _Hühnerauge_ versus _Hosenauge_	transparent = opaque, N400 for novel
Fiorentino, Naito-Billen, Bost, and Fund-Reznicek (2014)	English	single word presentation	lexical decision	visual	23 (19)	18–23/20	existing + novel 2-constituent	monomorphemic versus existing versus novel	_eggplant_ versus _throttle_ versus _tombnote_	N400 for novel

Zheng et al., (2015)	Chinese	associative recognition task	familiarity judgment	visual	20	–/22	existing + novel 2-constituent	existing: studied versus rearranged versus new	*Greek mythology* versus *Greek letter*	widespread N400 (300–700 msec)
								novel: studied versus rearranged versus new	*pool letter* versus *pool mythology*	widespread N400 (300–700 msec)
El Yagoubi et al., (2008)	Italian	single word presentation	lexical decision	visual	20 (18)	20–31/25	existing 2-constituent	compound versus non-compound with embedded word	*CAPObanda* versus *COCOdrillo*	LAN (270–370 msec) + late positivity for compounds
								left-headed versus right-headed	*CAPObanda* versus *astroNAVE*	P300 + late positivity
Arcara et al., (2014)	Italian	single word presentation	lexical decision	visual	24 (22)	19–36/21	existing 2-constituent	left-headed versus right-headed versus exocentrix	*PESCEspada* versus *astroNAVE* versus *cavatappi*	LAN for right-headed = exocentric (stronger effect in split presentation)
Vergara-Martinez et al. (2009)	Basque	first word in sentence	silent reading	visual	23	–/20	existing 2-constituent	first low- versus high-frequent constituents	*Izenburu (Hh)* versus *Elizgizon (Lh)*	anterior negativity
								second high- versus low-frequent constituents	*Izenburu (hH)* versus *Eskularru (hL)*	N400
Stites et al., (2016)	English	sentence reading	silent reading	visual	21	18–23/19	existing 2-constituent	correct versus TL within-morphemes versus TL across-morphemes	*cupcake* versus *cupacke* versus *cucpake*	P600, TL within-morphemes = TL across-morphemes
MacGregor and Shtyrov (2013)	English	oddball	passive listening	auditory	20 (18)	19–36/24	existing + novel 2-constituent	opaque: low- versus high-frequent	*bridgework* versus *framework*	MMN, larger for high-frequent
								transparent: low- versus high-frequent	*deskwork* versus *homework*	MMN, low- = high-frequent; + N400
								transparent versus opaque	*teamwork* versus *patchwork*	N400, transparent more negative!

Notes. M = modality, a = auditory, v = visual.

conditions. Because within-morpheme and between-morpheme letter transpositions did not differ (and showed similar effects as misspelled words in sentence context do), the findings were taken to indicate general processing difficulty rather than morphological decomposition. The authors concluded that English compounds are accessed as whole-word units during sentence reading. The question remains, however, whether TL-effects may indicate whole-word versus constituent processing.

4.1.3. *Constituent order in single word presentations*

Some languages have the head of a compound in a fixed position. For example, languages such as English, German, and Dutch are right-headed, while languages such as Italian and Basque possess both left- and right-headed compounds. The following two Italian studies compare the effects of headedness on the processing of compounds, while the study on Basque compares the frequency effects of the first and second constituent on compound processing. El Yagoubi, Chiarelli, Mondini, Perrone, Danieli, and Semenza (2008) compared Italian left-headed (e.g., *CAPObanda*, 'band leader') and right-headed (e.g., *astroNAVE*, 'spaceship') compounds with non-compounds that included left-embedded words (e.g., *cocco*, 'coconut' in *COCCOdrillo*, 'crocodile') or right-embedded words (e.g., *ruga*, 'wrinkle' in *tartaRUGA*, 'tortoise'). Relative to the non-compounds, compounds elicited an early starting negativity (LAN, 270–370 msec) that continued until 800 msec post-onset and thus formed a P600 for non-compounds. The LAN effect by compounds was interpreted as decomposition process, while the P600 of non-compounds was taken to indicate reanalysis due to the embedded words. Furthermore, right-headed compounds elicited a P300 that continued into a late positivity (300–800 msec) relative to left-headed compounds. The authors suggested that this effect may indicate that left- and right headed compounds differ in the attentional resources they require, with left-headed compounds using less resources, because they represent the more canonical word order in Italian sentences. In a follow-up study, Arcara, Marelli, Buodo, and Mondini (2014) compared left- and right-headed noun–noun compounds with exocentric verb-noun compounds (e.g., *salvagente*, 'life jacket') where neither the verb nor the noun is the head. To enforce the usage of attentional resources, compounds were presented as one word or split into constituents. Right-headed and exocentric compounds elicited LAN effects relative to the left-headed compounds. As in the previous study, the increases in the LAN effects were taken to reflect the working memory load rather than morphosyntactic operations.

Vergara-Martinez, Dunabeitia, Laka, and Carreiras (2009) presented Basque sentences starting with a compound. Compounds were manipulated for high and low frequency of the first and the second constituent. First constituents elicited an anterior negativity (300–700 msec) when they were of high frequency (relative to low-frequency first constituents), while second constituents elicited an N400 effect when they were of low frequency (relative to high-frequency second constituents). These findings were interpreted in the activation-verification framework by Duñabeitia, Perea, and Carreiras (2007): The first constituent triggers the activation of different candidates, and the higher the frequency the more candidates will be triggered. The second constituent triggers the selection of the final candidate, and the higher the frequency of the second constituent the easier the selection or verification process will occur.

4.1.4. *Novel versus transparent versus opaque*

In a long-lag repetition priming paradigm, Kaczer, Timmer, Bavassi, and Schiller (2015) compared the facilitation effects of existing compounds (e.g., *appelmoes*, 'applesauce') and novel compounds (e.g., *appel gezicht*, 'apple face') on overt picture naming (e.g., *apple*, 'apple'). Both existing and novel compounds induced N400 deflections relative to the unrelated condition, with marginally larger effects for novel than for existing compounds. These findings were interpreted to reflect that participants focus more on the constituents in novel than in existing compounds.

In addition, a study in English by Fiorentino, Naito-Billen, Bost, and Fund-Reznicek (2014) compared the processing of monomorphemic words (e.g., *throttle*), existing compounds (e.g., *eggplant*), and novel compounds (e.g., *tombnote*). They found widespread and long-lasting N400 effects (300–800 msec): relative to monomorphemic words, existing compounds were slightly more negative-going, while novel compounds elicited a strong negativity. Surprisingly, the N400 by novel compounds was even more pronounced than the N400 induced by nonwords (e.g., *blenyerp*). The authors interpreted the findings to indicate decomposition and combinatorial processes for existing and novel compounds.

Zheng et al. (2015) asked their participants to study existing and novel Chinese compounds and tested their associative recognition memory in a test phase. Relative to previously studied compounds, existing and novel compounds that were unstudied or with their constituents rearranged elicited widespread N400 negativities. The authors interpreted old/new effects in terms of familiarity and recollection processes to associative memory.

Some studies compared the processing of semantically transparent versus opaque compounds; however, as with derivational processing, transparency effects may be language specific. For example, in a study on Dutch compounds, Koester and Schiller (2008) applied a long-lag repetition priming paradigm and compared the effects of transparent compounds (e.g., *eksternest*, 'magpie nest') and opaque compounds (e.g., *eksteroog*, 'corn') on picture naming (e.g., *ekster*, 'magpie'). They found N400 deflections for picture naming following transparent and opaque compounds relative to unrelated or form-related words. Importantly, the N400 effects were equivalent for transparent and opaque compounds. These results showed morphological priming that is not modulated by semantic transparency and were interpreted to indicate that morphological priming facilitates language production at the word form level.

Additionally, a more recent study on German compounds replicated the lack of semantic transparency effects, together with a strong effect for novel compounds. Eulitz and Smolka (2017) compared compound triplets that held the same head (e.g., '*eye*'): transparent compounds (e.g., *Hundeauge*, 'dog's eye'), opaque compounds, (e.g., *Hühnerauge*, 'corn'; literal: 'hen's eye'), and novel compounds (e.g., *Hosenauge*, 'trouser's eye'). Novel compounds showed an N400 effect relative to existing compounds (with an earlier onset for good than for bad performers). However, the ERP effects by transparent and opaque compounds were equivalent and replicated behavioral findings (Smolka & Libben, 2017) that indicated constituent access regardless of the transparency of the whole-word compound. The authors concluded that the brain of German speakers differentiates between familiar and novel word composition, but not between transparent and opaque meaning composition.

MacGregor and Shtyrov (2013) applied a passive-listening oddball paradigm to explore compound processing in English by means of the auditory MMN. They compared transparent (e.g., *homework*) and opaque compounds (e.g., *framework*) of high and low frequency to novel compounds (e.g., *houndwork*). For opaque compounds, they found a frequency effect (i.e. larger MMNs to high-frequent than low-frequent compounds), which was interpreted as the "lexical MMN" that indicates the activation of whole-word representations of known words. By contrast, the MMNs for transparent compounds showed no frequency effect and were thus interpreted as "syntactic MMNs", which are considered to index combinatorial processing (see e.g., Bakker et al., 2013). Note, however, that the MMNs for (high- and low-frequency) transparent compounds were similar to the MMN of high-frequency opaque compounds. Additional N400 effects showed the expected frequency effect in terms of more negative amplitudes for low-frequent than for high-frequent compounds, an inversed transparency effect with more negative going amplitudes for transparent than for opaque compounds, and a lexicality effect with more negative amplitudes for novel as compared to high-frequent transparent compounds. The authors concluded that opaque compounds are accessed as whole-word units, while both whole-word access and combinatorial processing apply to transparent compounds.

Overall and across different languages, most of the above findings (with few exceptions from English) point to the role of morphological decomposition in compound recognition and production, with headedness and the frequency of constituents playing an important role.

4.2. MEG

To the best of our knowledge, there are only two MEG papers on compound processing, see Table 8. Fiorentino and Poeppel (2007) employed a visual lexical decision task comparing compounds (*flagship*), single words (*crescent*), and pseudomorphemic controls (*crowskep*). They found a significantly earlier M350 peak latency for the compound words than the single words, which was taken to suggest that compounds were processed by decomposition. Tentative source modelling revealed activation in the temporal area. Pseudomorphemic controls did not differ significantly from compound words, which gave a reason to suggest that they were processed more as compounds than as simple words. Hence, the results were interpreted to support early morphological parsing of compounds. More recently, Brooks and Cid de Garcia (2015) examined the processing of transparent compounds (e.g., *roadside*), opaque compounds (e.g., *butterfly*), and morphologically simple words (e.g., *spinach*) in a word naming task,

Table 8 – *Summary of MEG studies on compounds. The studies used single word tasks.*

Study	Language	Task	Modality	Sample size	Age range/mean age	Grammatical category	Comparison	Effects and their neural sources
Fiorentino & Poeppel, 2007	English	Lex dec	Visual	12	18–26	Noun	Compound > Simple Compound > Pseudocomplex foils	M350; exploratory source analysis: left temporal area
Brooks & Cid de Garcia, 2015	English	Word reading and naming	Visual	18	18–30	Noun	Transparent > Simplex Opaque > Simplex	LATL (250–470 msec), pSTG (430–600 msec)

which involved priming. For the partial-repetition priming, the first constituent of the compound was used as the prime (e.g., tea-teacup). For the simplex word condition, the non-morphological related form was used as the 'constituent' prime (e.g., spin-spinach). There were also two control conditions, in which the prime had no semantic relationship to the target (e.g., doorbell-teacup; door-teacup) as well as a full repetition priming condition (e.g., teacup–teacup). Cluster permutation statistics for the neural sources revealed two significant clusters associated with transparent compound versus simplex word difference. That is, the first cluster was localized to the anterior middle temporal gyrus (in the 250–470 msec time-window), and the second one to the posterior superior temporal gyrus (430–600 msec time-window). Hence, compound processing was suggested to involve a decomposition stage that is independent of semantics, and a composition stage involving semantic processing. However, there was no explicit discussion of the lack of differences between opaque compounds and simplex words. The authors briefly mention that the differentiation between opaque and transparent compounds might take place at a later level of morphological composition. Together, these very scarce findings point to the role of morphological decomposition in compound recognition and production, with temporal area playing a significant role in the compound processing.

4.3. *fMRI*

The literature on the processing of compounds with fMRI comprises only a handful of studies with a variety of methods and research questions, which are summarized in Table 9. For example, the earliest study to look at compounds (Koester & Schiller, 2011) was conducted in Dutch, and revealed greater activation of the LIFG in conditions when the first part of a compound primed a picture, compared to conditions with unrelated primes. This effect was observed regardless of the semantic transparency of the compound, suggesting that compounds in Dutch are automatically and by default decomposed. Further to that, Forgács et al. (2012) showed increased bilateral frontal and temporal activation for the processing of known compounds in German when compared to novel but phonologically valid compounds, while the latter increased LIFG activation. The authors interpreted this pattern as evidence for semantic processing of the already known forms, compared to active combination of phonological, syntactic and semantic information for both components of the novel compounds in order to result in some meaning. Finally, more recently Zou, Packard, Xia, Liu, and Shu (2016) tested processing of compounds in Chinese with compound pairs that were either (a) identical, (b) phonologically related, (c) phonologically *and* orthographically related, or (d) phonologically, orthographically *and* morphologically related. Their results suggested that, while all types of compound pairs activated the LIFG, this activation was modulated by the degree of relatedness between the two compounds, with the latter condition causing the highest activation. The scarcity of the available evidence makes it obvious that no conclusions can be drawn for the

Table 9 – Summary of fMRI studies on compounding. Only findings related to morphological decomposition are reported.

Study	Language	Task	Modality	Sample size	Age range/ mean age	Grammatical category	Comparison	Activated brain regions
Comprehension tasks								
Forgács et al., 2012	German	Covert reading with familiarity judgement	visual	40	19–30	nouns	Known (literal and metaphorical) > novel compounds Known (literal and metaphorical) < novel compounds	L: ITG, MFG, AG, SFG R: MFG, SMG, MTG, AG, STS, STG, SFG, precuneous L: IFG, INS, SMA, FFG R: INS, SMA
Zou et al., 2016	Chinese	First syllable similarity judgment in word pairs	auditory	17	M = 21.24, SD = 1.75	nouns	Pairs with morphological, phonological and orthographic relationship > identical pairs Pairs with morphological, phonological and orthographic relationship > pairs without morphological relationship only	L: IFG, MTG, FG L: IFG,
Production tasks								
Koester & Schiller, 2011	Dutch	Delayed priming with picture naming	visual	12	19–29	nouns	Primed (transparent & opaque)> unrelated	L: IFG

processing of compounds from fMRI, highlighting the need of further studies.

5. Summary and future directions

The current review of the neuroimaging literature on the different morphological operations leaves a bittersweet taste. On the one hand, it is evident that there is a good deal of studies exploring morphological decomposition of inflected and derived (and, to a lesser extent, compound) words, demonstrating an increasing interest from cognitive neuroscientists in how, when and where morphological processes take place in the brain. However, on the other hand, this vast number of studies offers a fuzzy general picture about the mental operations underlying morphological processing, given that there is a notorious lack of consensus across research reports, and the different results sometimes offer some mismatching pieces of a jigsaw puzzle.

The most consistent set of data across neuroimaging techniques (and hence, the "good" in the title of this article) corresponds to the processing of inflectional morphology. With some exceptions (see the corresponding section for further details), most studies seem to support accounts based on dual mechanisms in charge of processing regular and irregularly inflected forms, in line with the categorical differentiation proposed by Ullman et al. (1997, 2005). The majority of EEG, MEG and s/fMRI studies support a distinction based on the memory systems underlying regular and irregular polymorphemic inflected word processing (procedural and declarative memory systems, respectively). The timing differences reported in most EEG and MEG studies speak for an earlier access to and decomposition of regular inflections than of irregular forms (even though it should be clearly noted that this is not the case in all studies). In a similar vein, many EEG, MEG and fMRI studies provide topographical evidence favoring a clear-cut distinction in the distribution of the morphological processing of regular and irregular forms, with general morphological operations taking place for all inflected words in left fronto-temporal and parahippocampal regions, and specific brain areas that have been classically linked to the procedural memory network (see Ullman, 2004) being recruited for the processing of regular inflections (e.g., the left IFG, and arguably, MFG, the basal ganglia and the cerebellum).

The picture offered by the review of the studies investigating derivational morphology is much hazier (and hence the "bad" in the title) than the review of inflectional morphology. Most of the studies suggest that the activation and response patterns support decompositional, two-stage (orthographic and semantic) or dual-route accounts, but the latency of morphological effects as well as their localization differ greatly depending on the paradigm and linguistic variables. While some EEG and MEG studies suggest that the decomposition of truly derived word forms occurs at around 200 msec after being presented with the target item (N250 and M170 effects), other studies using similar paradigms with the same techniques have suggested that significant morphological priming effects can be only found after this epoch (e.g., in the M250 time-window or later). Similarly, some MEG and fMRI studies advocate for morphological effects taking place at left occipito-temporal areas, whereas other studies differentiate between the topographical effects of truly derived and pseudoderived word decomposition, pointing to the left IFG as a critical area involved in the processing of derived words. Hence, the processing of derivationally complex words involves a network of regions, spanning from stimulus modality-specific areas to the core language-related fronto-temporal regions that are currently under debate. It is obvious, however, that much more evidence is needed to form a comprehensive view on derivational processing, using more uniform paradigms, stimulus properties, and perhaps even direct cross-linguistic comparisons. In light of the present evidence it is challenging to construct a fully detailed spatio-temporal map of how derived words are processed and what are the exact neural signatures of morphological decomposition.

Lastly, the short review of the few studies exploring compound word processing demonstrates that this is one of the key morphological operations that requires further attention and that needs to be developed given the scarcity and volatility of the results (and hence the "ugly" in the title). While some studies clearly support views favoring the access to the constituent morphemes prior to accessing the whole compound word, some other neuroimaging studies posit that compounds are processed at a whole-word level. Moreover, while some studies suggest that the semantic transparency of compound words may determine the manner in which these words are accessed, others claim that transparent and opaque compounds are processed similarly. Furthermore, there are studies suggesting that the extent to which constituents can be accessed highly depends on the prior experience with the whole compound, claiming for differences in the morphological decomposition of novel and existing compounds.

This review was intended to present the readership with a panoramic view of how the field of cognitive neuroscience has embraced the study of morphological processing, highlighting the consistencies and discrepancies across studies and techniques. The readers should be aware of the difficulty of cataloguing such an impressive amount of neuroimaging studies on the different morphological operations. If we had to summarize in just a sentence the most consistent set of results across the three morphological operations (inflection, derivation and compounding) and the three neuroimaging techniques (EEG, MEG and MRI), we would conclude that the processing of morphologically complex transparent words that allow for a clear (rule-based) identification of their morphemes starts as early as ~200 msec and recruits areas of the left IFG, as compared to the slightly later, and more widespread, processing of other types of opaque polymorphemic words. But this is admittedly an oversimplification of a much more complex picture, so we maintain that despite the large amount of studies investigating how morphology is represented and processed in the brain, more studies are definitely needed.

However, we want to stress that we are not advocating for uncritical replications or extensions along the same lines, since it is relatively evident from this review that the field does not desperately need such studies. The complexity of understanding how complex words are processed may require a different approach, and it is worth considering some of the possible reasons for some of the critical inconsistencies found across studies that have been highlighted in the current review.

First, studies should focus on and account for interlinguistic differences, and while the Anglo centrism governing the literature of morphological processing has been useful to set the grounds of a field, researchers should take into account that when it comes to exploring the neural underpinnings of morphologically complex word processing, other languages with richer morphological systems may provide interesting alternatives. As we have discussed above, some of the potentially conflicting pieces of evidence may result from cross-linguistic differences, as a natural consequence of the morphological architecture that defines each language. Morphological operations do not necessarily imply parallel processes across languages (see Belletti, Friedmann, Brunato, & Rizzi, 2012; Guasti, Stavrakaki, & Arosio, 2012; Vannest, Bertram, Järvikivi, & Niemi, 2002). Hence, the search of universal models of morphological processing may be chimera, or at least, a feat that could only be achieved if cross-linguistic differences in the development and processing of morphological complexity are explored by investigating typologically different languages. Purely analytic languages such as Chinese and moderately analytic languages like English that have relatively simple inflectional systems and that prioritize the use of individual words instead of affixes to mark grammatical relationships are in clear-cut contrast with synthetic languages, which favor the use of affixing for word creation, including fusional languages like Hebrew or Arabic, and agglutinative languages like Finnish or Basque. With this in mind, it seems rather logical that any search for a universal model of morphological processing will necessarily require discriminating between cognitive processes that respond to the idiosyncratic morphological characteristic of some languages and those that respond to common morphological features across linguistic systems (see Frost, 2012, for a discussion on a similar cross-linguistic debate on visual word recognition). For example, a recent computational model has shown that the behavioral differences in morphological processing in English and German can be explained by the different language structures of (morphologically more analytic) English versus (morphologically more synthetic) German (Günther, Smolka, & Marelli, 2018). That is, the cross-linguistic effect can be attributed to quantitatively-characterized differences in the speakers' language experience.

Second, and in a related vein, neuroscientific research should also target more consistently other types of morphologically rich words, like those including prefixes or infixes, or those concatenating more than two morphemes. Any general claim about morphological decomposition and parsing should be also able to account for polymorphemic words above and beyond suffixed words.

Third, the individual differences across polymorphemic items and across participants need to be dealt with in neuroscientific studies as it is being explored in other domains too. There are myriads of morphologically complex words with their own sub-lexical, lexical and supra-lexical properties. Similarly, there are multiple cognitive skills, constructs and traits that can modulate the manner in which a person accesses polymorphemic words. Hence, a coherent and unitary approach should be able to account for all these particularities of the persons and the words, and current statistical approaches allow for fine-grained analyses at this regard.

And fourth, we propose that future large-scale studies should try to replicate the findings not only across languages, but also across modalities (e.g., visual *vs.* auditory), across paradigms (e.g., masked *vs.* unmasked priming; single-word versus multi-word processing), not forgetting the need for the development of more ecologically valid and natural paradigms and stimuli. Future studies should also attempt to replicate findings across neuroimaging techniques, and combination of different methods is now possible and therefore, highly encouraged (e.g., combined EEG and fMRI, combined EEG and MEG, eye-fixation related potentials/fields).

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