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# Compound Words Are Decomposed regardless of Semantic Transparency and Grammatical Class: an fMRI Study in Persian

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## Abstract

Processing of morphologically complex words in the brain is a sophisticated phenomenon. In this study, we asked whether the semantic transparency of compound words and their grammatical class played a role in their processing at the neural level in Persian, a language with a relatively productive system of morphological compounding. Twenty-eight native speakers of Persian performed an auditory task during fast-sparse fMRI. Combined univariate and multivariate analyses showed that all compound words were processed similarly regardless of their semantic transparency and grammatical class. Our findings partially support those approaches that claim semantic transparency is a property of processing, not representation. We contend that language-specific properties such as linguistic productivity and task-related manipulations are very important in modulating morphological processing.

Key words: Auditory, Compound, fMRI, Persian, Semantic Transparency

## 1. Introduction

How are complex words recognized during natural language comprehension? Complex words are words which consist of at least one or two roots and one and more affixes. For example, the words “helpful” and “snow man” are complex words. In the former, a root is combined with an affix, while in the latter two roots are combined to form a compound word. One debate concerns whether complex words are represented in the neuro-cognitive system as a single unit or decomposed into individual constituents (Brooks & Cid De Garcia, 2015; Giraudo & Grainger, 2001; Taft, 2004). “Full-listing” theories suggest that all complex words are represented in their full forms (Butterworth, 1983; Bybee, 1995). On the other hand, the “full-parsing” theories postulate that all complex words are decomposed into their smaller building blocks during language processing (Libben, Derwing, & de Almeida, 1999; McKinnon, Allen, & Osterhout, 2003; Taft, 2004; Taft & Forster, 1976). A third theory called “dual-route” posits that complex words could be processed both wholistically and decompositionally depending on variables such as semantic transparency and frequency (Baayen, Dijkstra, & Schreuder, 1997; Bertram, Laine, Harald Baayen, Schreuder, & Hyönä, 2000; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Schreuder & Baayen, 1997). Semantic transparency, henceforth transparency, is the topic of this study.

In this study, transparency is defined in terms of “the extent to which the constituents of compounds maintain their whole word meaning within the compound structure” (Libben, Gagné, & Dressler, 2020), p. 340; see (Ji et al., 2011; Kim, Yap, & Goh, 2018; Pollatsek & Hyönä, 2005; Sandra, 1990; Zwitserlood, 1994). For example, “*Milkman”* is semantically transparent because the meaning of the compound (a man delivering or selling milk) is related to both “*milk”* and “*man”*, whereas “*dustman*” is less transparent in English reflecting the lack of continuity in relatedness (Jackendoff & Wittenberg, 2014).
There are two main approaches towards how transparency affects compound processing: the conjunctive activation approach and the meaning construction approach (El-Bialy, Gagné, & Spalding, 2013). In the former, transparency is a representational property. A distinction is being made between the lexical and semantic levels of representation in this approach, and the links between these levels determine whether transparency has a facilitatory or inhibitory effect. According to this approach, a processing cost (inhibition) occurs for those compounds which lack links between lexical and semantic levels of representation, which is the case for opaque compounds. On the other hand, the meaning construction approach thinks of transparency as a processing property. Based on this approach, the links between lexical and semantic levels exist for both transparent and opaque compounds. According to this account, compound words undergo two stages during language comprehension: decomposition and integration (Gagné & Spalding, 2009; Inhoff, Radach, & Heller, 2000; Ji, Gagné, & Spalding, 2011). In a decomposition stage, all complex words are broken down into their constituents regardless of their semantic transparency. This happens because of the incrementality of language processing. The language system has to access the meanings of all constituents of a compound first before making any decisions upon the contribution of these constituents to the final meaning of the compound. In the integration stage, the language system has to check the computed meaning from previous stage against the conventional meaning of the compound in the mental lexicon. At this level, a processing disadvantage occurs for opaque compounds because the computed meaning does not match with the conventual meaning forcing the system to spend time recovering the correct meaning (Ji et al., 2011).

Both mentioned approaches have been proposed in the context of behavioural studies. A dual neurobiological framework which tries to account for the neural computations underlying complex words is proposed by Marslen-Wilson, Bozic, and Tyler (2014). Based on this framework, two complementary neural systems are hypothesized to allow the comprehension of complex words: a domain-general neural network including the bilateral temporal regions that supports sound-to-meaning mapping during comprehension; and a domain specific, left lateralized fronto-temporal network that is necessary for morphosyntactic processing (Tyler & Marslen-Wilson, 2008). Inflectional morphology, which is considered to be combinatorially more complex, is expected to induce more activity in the left hemisphere fronto-temporal network, while the less complex processing of derivational morphology is expected to engage bilateral temporal regions (Klimovich-Gray et al., 2018). Within this framework, however, it is predicted that the two different brain networks will be modulated by several factors such as combinatorial complexity, productivity and semantic transparency (Bozic, Fonteneau, Su, & Marslen-Wilson, 2015; Carota, Bozic, & Marslen-Wilson, 2016). In a study on Italian morphological decomposition, Carota et. al., (2016) showed that opaque morphological forms were mainly processed in bilateral fronto-temporal regions, while, transparent forms engaged the left inferior frontal regions more extensively. Marslen-Wilson and colleagues have reported findings in several languages to support their hypothesis (see Boudelaa, Pulvermuller, Hauk, Shtyrov, & Marslen-Wilson, 2010; Bozic et al., 2015; Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Carota et al., 2016). This framework has been tested with derivational and inflectional morphology. It would be interesting to test the predictions of this framework with compound words.

Research on compound words has focused mainly on several European languages including German, French, English, Finish, and Italian (Leminen, Smolka, Duñabeitia, & Pliatsikas, 2018). Neuroimaging studies of morphological processing in non-European languages are very rare despite similar roots in the Indo-European language tree. We decided to study Persian because it has a highly productive system of compounding (Family, 2014; Author et al., 2016). Languages with a high degree of productivity in their compounding system offer a unique ground to test current theories of compounding (Duñabeitia, Laka, Perea, & Carreiras, 2009). For example, one common feature of Persian is lack of simple verbs and the abundance of Light Verb Constructions (LVC). Unlike many languages which use simple verbs to convey action meanings, in Persian usually a noun, adjective or prepositional phrase is combined with a light verb to convey meaning. Take the LVC "رنگ زدن" ("paint hit" meaning "to paint"). Paint as a noun is combined with hit as a verb to create the final meaning of the compound.

The majority of previous studies have focused on compound nouns which limits the generalizability of findings to other compound types. It is an open question whether the grammatical class (GC) of a compound, being a noun or a verb, plays any role in the way they are represented and processed. Previous research on non-compound nouns and verbs have revealed mixed findings (Siri et al., 2008; Vigliocco et al., 2006). We decided to study LVCs and Noun-Verb Compounds (NVC). We use the term Light Verb Construction (LVC) for compound verbs and Noun-Verb Compounds (NVC) for compound nouns and adjectives. Both LVCs and NVCs are semantically very similar consisting of a noun and a verb. However, they belong to different GCs. LVCs are syntactically categorized as verbs, and NVCs are considered either nouns or adjectives. An example of NVC is "آدم کش" ("person kill" meaning an "assassin"). For the example of an LVC refer to the previous paragraph.

The specific goal of this study is to examine the role of transparency and grammatical class in the processing of compound words in Persian speech recognition using auditory fMRI. We hypothesize if transparency is a representational property predicted by conjunctive activation approaches, we should see neural differences in the processing of opaque and transparent compounds. This is because the links between lexical and semantic levels of a compound representation are static (El-Bialy et al., 2013) and task-related manipulations have no effects on how transparency will be represented in the brain. Based on predictions from the dual neurobiological framework (Marslen-Wilson et al., 2014), transparent compounds should engage the left fronto-temporal network more extensively than opaque compounds because they are more complex. On the other hand, if transparency is a property of processing (see Ji et al., 2011; Author et al., 2021), we should not see any differences between transparent and opaque compounds in the decomposition phase because based on predictions from construction meaning approaches; all compound words are first decomposed regardless of their transparency level (Gagné & Spalding, 2004, 2009). However, we were not sure whether our task, a passive listening task, would be able to pick up the difference at the integration phase given that it lacked an explicit response function. The reason for this uncertainty was lack of prior neuroimaging research in this regard. However, we should mention that our prior behavioural work (Author et al., 2021) did not find a difference even in the presence of a response function. We used a masked priming with three different SOAs in that study.

A second prediction in this study concerns the grammatical class (GC) effect. We hypothesize that the GC of a compound word will not affect how it will be processed particularly because the semantic properties of both compound types were very similar in this study; both compound types used in this study consisted of a noun and a verb. This prediction is based on two prior studies in Persian. Author et al., (2016) did an fMRI study on noun and verb processing using a sentence completion task. They controlled semantic and visual properties of words such as imageability, visual complexity, familiarity, frequency, and Age of Acquisition. Their findings revealed that nouns and verbs were processed similarly in the brain when semantic properties were controlled. In another behavioral study, Author et al., (2021) used a masked priming to look at the effects of transparency and GC. Their findings revealed that both transparent and opaque compound words were processed similarly regardless of GC.

## 2. Methods

### 2.1 Participants

Twenty-eight native Persian speakers (10 female, age mean = 26, education mean (number of years) = 16.5) were recruited from Iran. A language history questionnaire was administered to make sure Persian was their native language and that they communicated via Persian on a daily basis. All participants were right-handed. No participant had a history of neurological disorders and none were taking any medications which might create changes in the blood flow or pressure. We obtained written informed consent from all participants before data collection. We received Ethical Approval from the National Ethics Committee at Iran.

### 2.2 Stimuli and Procedure

In this study, transparency is defined in terms of “the extent to which the constituents of compounds maintain their whole word meaning within the compound structure” (Libben, Gagné, & Dressler, 2020), p. 340; see (Ji et al., 2011; Kim, Yap, & Goh, 2018; Pollatsek & Hyönä, 2005; Sandra, 1990; Zwitserlood, 1994). For example, “*Milkman”* is semantically transparent because the meaning of the compound (a man delivering or selling milk) is related to both "*milk"* and "*man"*, whereas "*dustman*" is less transparent in English reflecting the lack of continuity in relatedness (Jackendoff & Wittenberg, 2014).

The subjective familiarity and semantic relatedness of NVCs were rated by 28 and 32 native Persian speakers respectively and the familiarity and semantic relatedness of LVCs was rated by 49 and 33 different Persian speakers. We used Intra-Class Correlation (ICC) to measure the consistency of rating among participants. The results of a two-way random effects models and average raters unit revealed an ICC of 0.99 for both familiarity and relatedness ratings. Based on Koo and Li's (2016) recommendation, the ICC showed that the ratings were totally reliable. A one-way ANOVA found a significant difference in relatedness between the four conditions $F(3, 296) = 505.99$, $p < .001$. Further post-hoc tests showed that relatedness ratings for transparent NVCs and LVCs were significantly higher than opaque NVCs and LVCs ($p < .001$). A one-way ANOVA revealed no significant differences in familiarity ratings for the stimuli across transparent and opaque conditions $F(3, 296) = 1.38$, $p = .24$. We used Hamshahri2 corpus to extract frequency of the experimental words in Persian (Aleahmad, Amiri, Darrudi, Rahgozar, & Oroumchian, 2009). This is a large corpus consisting of several types of genres and documents. The results of one-way ANOVA were not significant ($F(3, 296) = 2.04$, $p = 0.10$) meaning the experimental stimuli were not different in their frequency of occurrence.

We acknowledge that it is not easy to distinguish between compound words from syntactic combinations or phrasal sequences. We ,therefore, used a metric of Mutual Information (MI) bigger than 3 to make sure that both constituents of NVCs and LVCs had a strong association (Hunston, 2002). MI measures the degree of dependency between the constituents. All compound words had an MI bigger than 3, and all stimuli used in the Control condition had an MI smaller than 3. The Control condition consisted of single words with inflectional morphology (apples), short phrases (This coffee) and short sentences (He jumped). We selected these stimuli as Control condition because previous research have shown that these stimuli are processed in a decompositional manner during speech recognition (Bozic et al., 2015; Carota et al., 2016; Schell, Zaccarella, & Friederici, 2017; Yang, Marslen-Wilson, & Bozic, 2017; Zaccarella, Meyer, Makuuchi, & Friederici, 2017). Comparing the compound words with the Control condition in their neural patterns is critical in this study because it would reveal whether compound words were processed decompositionally or not.

We used a listening paradigm accompanied by a one-back memory task in an attempt to keep the participants active and alert throughout the experiment (Carota et al., 2016; Yang et al., 2017). Every participant listened to the trials and in 7% of the stimuli they had to make a decision. They had to judge whether the stimulus they heard was semantically related to a word projected on the screen or not. They indicated their answer (yes or no) with a response grip provided in the scanner. We removed the trials related to one-back task from the analysis. The whole experiment consisted of 5 blocks of stimuli. Each block consisted of 142 different items. In every block we had 15 transparent LVCs, 15 opaque LVCs, 15 transparent NVCs, 15 opaque NVCs, 30 control stimuli (inflectional morphology, short two-word phrases and sentences such as "this book" and "he jumped"), 32 musical rain (MuR) samples used as acoustic baseline, and 20 silence samples. The stimuli were randomized within each block. Block order was randomized across all participants. Every block lasted about 10 minutes. Having a practice session before the scanning, we made sure the participants were properly briefed for the task.

We used MuR as the baseline because previous studies have shown that MuR captures acoustic properties of speech without producing an intelligible speech percept (Bozic et al., 2015; Bozic, Tyler, Ives, Randall, & Marslen-Wilson, 2010). We randomly selected 30 stimuli from each condition and then extracted their temporal envelope. The extracted envelopes were then filled with MuR by jittering 10ms fragments of vowel formants (Bozic et al., 2010; Uppenkamp, Johnsrude, Norris, Marslen-Wilson, & Patterson, 2006). The resulting MuR stimuli were matched in length with other conditions, and had the same long-term spectro-temporal distribution of energy.

### 2.3 Data Acquisition

Data were acquired using a 3T Siemens Prisma MRI Scanner at the National Brain Mapping Lab, Tehran. The imaging protocol was a fast-sparse gradient-echo EPI sequence (repetition time = 4 sec, acquisition time = 2 sec, echo time = 30 ms, flip angle =78°, matrix size = 64 × 64, field of view = 192 × 192 mm, 32 oblique slices 3 mm thick, 0.75 mm gap). This type of imaging allowed us to remove the effect of EPI noise during the presentation of auditory stimuli. Stimuli were presented within the 2s silence period between scans, and at least 200ms after the end of the previous scan to make sure there was no perpetual overlap between the stimulus and the scanner noise. T1 weighted high resolution images were obtained for anatomical localization (1×1×1 mm, TR = 1800; TE = 3.5; FOV = 256).

### 2.4 Data Analysis

### 2.4.1 Univariate Analysis

We used Freesurfer software for the univariate analysis. The pre-processing phase consisted of the following steps: reconstructing cortical surfaces using T1 images, registering functional images to structural images, motion correction and registration of all trials to middle trial of each run, and spatial surface-based smoothing (fwhm = 5mm). We did not use slice timing correction since it is not recommended for sparse sampling imaging (Perrachione & Ghosh, 2013). The smoothed images for each subject were analyzed using a general linear model. Five experimental conditions (Control, TNVC, ONVC, TLVC, and OLVC), along with MuR, Silence, and confounding regressors including motion regressors and 2nd order polynomial of time (to model signal drift) were added to the design matrix. A template haemodynamic response function (spm-hrf kernel) was convolved to the regressors of interest. A general linear model was fitted for each run. Contrast images from single subject level analysis were combined into a group random effects analysis. The results are presented at FDR $p < 0.05$ level corrected for multiple comparisons.

### 2.4.2 Representational Similarity Analysis

RSA is a technique for analyzing neural imaging data that works based on comparing(dis)similarity in patterns of activation in the brain between multiple conditions with hypothesized models (Kriegeskorte, Mur, & Bandettini, 2008; Nili et al., 2014; Walther et al., 2016). RSA is motivated by cognitive models to test explicit hypotheses and also to explore how different brain mechanisms are computed (Klimovich-Gray & Bozic, 2019; Lyu et al., 2019). We used a searchlight approach to assess patterns of activity in whole brain (Kriegeskorte et al.

2008; Nili et al. 2014). In addition to parameters for motion and drift, average white matter and CSF time courses were regressed out from the data. For each gray matter vertex, the 27 closest vertices were selected as neighbours to form the searchlight followed by calculation of a condition by condition data representational dissimilarity matrix (called a data RDM) by computing Euclidean distance between the activity pattern of each pair of conditions in that searchlight. Each cell in the RDM shows the dissimilarity in the activation patterns between pairs of conditions. We averaged RDMs across all participants. These brain data RDMs were then compared with hypothesized model RDMs using Pearson correlation. For group level inference t-test against zero was computed for each vertex and corrected for multiple comparisons using FDR correction.

## 3. Results

### 3.1 Univariate Results

We subtracted MuR (baseline) from all stimuli to show the pattern of activity for speech-driven syntactic and lexical processing. This defines the core language system including areas such as the left superior and middle temporal gyri (STG/MTG), left inferior frontal gyrus (LIFG), and right STG (Figure 1) (Bozic et al., 2010; Hagoort & Indefrey, 2014; Hickok & Poeppel, 2007; Klimovich-Gray & Bozic, 2019).

Insert Figure 1 here

Figure 1: Significant activation in the core language system

To show the brain regions which were differentially activated as a function of transparency and GC, we performed a transparency (transparent vs. opaque) by GC (LVC vs. NVC) ANOVA. The results of the analysis revealed neither any main effects for either transparency or GC nor any interactions. This suggests that all compound words activated similar brain regions regardless of their transparency and GC. In the next analysis, we compared all compound types with the Control condition to see whether compound words were processed decompositionally just like Control condition or not. The results of the analysis did not show any significant differences between the conditions suggesting that Persian compound words, words with inflectional morphology, short phrases, and simple sentences were all processed similarly.

### 3.2 RSA Results

RSA offers a more sensitive method to detect expected differences according to a pre-defined theoretical model. RSA was used to find out whether any areas in the brain would show preferential activation for a specific contrast or computation. We designed several theoretical RDMs with each one testing a specific hypothesis (Figure 2). The first model (Language Model, Figure 2, a) tested which areas show sensitivity to linguistic stimuli. Consistent with the Univariate analysis, RSA analysis revealed activity patterns in core linguistic areas of the brain. Model b (Compound Model) was performed to identify areas that are sensitive to variability in morphological compounding across stimuli. The model assumes that each compound word triggers an activity pattern similar to other compound types, but different to other conditions such as Control or MuR. In line with the Univariate analysis, no brain areas showed any selective activation for compound word conditions. In the next model (Transparency Model, model c), we tested the effect of compound transparency on brain computations. In this model, transparent compounds were combined together regardless of grammatical class. RSA revealed no regions in the brain that showed sensitivity to semantic transparency. This finding was also consistent with the Univariate findings. In the final two models (models d and e), we tested whether any brain regions are sensitive to grammatical class of the compound words. In model d, NVCs were grouped together, and in model e, LVCs were clustered together. We did not find any significant activity patterns which fitted with these model RDMs. This meant that the syntactic class of a compound did not play a role in its processing and representation.

Insert Figure 2 here

Figure 2: Detector model RDMs, O stands for opaque and T stands for transparent before each acronym

## 4. Discussion and Conclusion

The goal of this auditory fMRI study was to test the hypothesis whether semantic transparency of compound words and their grammatical class would influence the way they were processed. Our findings suggest that all Persian compound words, regardless of the grammatical class and transparency, activate the same brain regions. Persian compound words are processed similar to other stimuli that are processed decomposionally in speech perception (Bozic et al., 2015; Carota et al., 2016; Schell et al., 2017; Yang et al., 2017; Zaccarella, Meyer, et al., 2017).

Evidence of semantic transparency effects on neural activation is scarce and existing findings are mixed (Leminen et al., 2018). An EEG study of English compound words showed an effect of transparency with a passive-listening oddball paradigm (MacGregor & Shtyrov, 2013). Their results showed that for opaque compounds in English, there was evidence of holistic processing, whereas for transparent compounds, there was evidence of both holistic and decompositional processing. In contrast, EEG studies of Dutch compound words show a different pattern. At least two studies reported that N400 effects were similar for both opaque and transparent compounds (Eulitz & Smolka, 2017; D. Koester & Schiller, 2008). An fMRI study of Chinese words compared compounds with different degrees of semantic relatedness in sound and meaning (Zou, Packard, Xia, Liu, & Shu, 2016). They found an increase in LIFG activation as the degree of relatedness increased. Another fMRI study of Dutch compound words found neural priming effects in the LIFG for all compound types regardless of their semantic transparency (Dirk Koester & Schiller, 2011).

Previous behavioural studies have shown that transparency effects depend on the type of the task and manipulations adopted in the study (Frisson, Niswander-Klement, & Pollatsek, 2008; Juhasz, 2018; Kim et al., 2018). We used an auditory task in our study. An auditory task is different from a reading task in that it is more incremental in nature (see Lyu et al., 2019; Zwitserlood, 1989). In comparison with reading where the parafoveal view gives readers an awareness of the surrounding words, in listening tasks the words are gradually unfolding over time (see Gaskell & Marslen-Wilson, 1997; W. D. Marslen-Wilson, 1987). One challenge for theories that posit differential direct route processing for opaque compounds is to explain how the language processor predicts in advance whether the upcoming combination of words is opaque or not (Bell

& Schäfer, 2016). Whether the combination of upcoming words forms an opaque or transparent compound, the language system is still forced to access a sizeable portion of the compound word before the uniqueness or recognition point is realized (Marslen-Wilson & Tyler, 1980). In this regard, our findings are more compatible with the predictions of a meaning construction approach at least when it comes to the decompositional stage of compound processing. Based on this approach, transparency is not a property of representation. All spoken compound words undergo a process of 'decomposition' regardless of their ultimate transparency realized during recognition (Inhoff et al., 2000; Ji et al., 2011; Author et al., 2021). However, transparency effects emerge at a later stage called 'integration'. When the computed meaning does not match with the realized whole-word meaning, which is normally the case with opaque compounds, a transparency effect may be observed. One explanation for this lack of effect in the integration level in our study could be an absence of a response factor in our auditory task: since no response or decision was expected in the task, no conflict had to be resolved. It is important to note that the majority of prior studies showing transparency effects at the integration level have used a task where the conflict had to be resolved explicitly such as a lexical decision task (see Libben et al., 2020). There is also the possibility that the transparency effects at the integration level might only be observed in the form of processing demands or temporal effects. As fMRI has very low temporal resolution, it is not ideal for testing temporal effects of transparency in listening, but this could be done with techniques such as MEG which has both an acceptable level of temporal and spatial resolution.

Peculiar properties of the Persian language such as productivity could also account for the lack of difference between opaque and transparent compounds. The fact that we did not find any effects for transparency is compatible with findings from German and Dutch. German and Dutch are morphologically rich languages which have a very productive system of compounding (Smolka, Libben, & Dressler, 2019). Persian shares this property with German and Dutch. We believe productivity of compound constituents could override any potential effect of transparency (see on German (Smolka & Libben, 2017; Smolka et al., 2019). For a word to become highly productive (systematic) in a language, it must have been processed with a high amount of parsing (Hay & Baayen, 2002). This creates a "lexical processing style" in which "native speakers abstract a constituent structure regardless of the meaning of a particular whole-word compound" (Smolka & Libben, 2017, page.16; Smolka et al., 2019). This means speakers of Persian language process the compound words decompositionally regardless of transparency level of the word. This productivity effect is also evident in other types of complex words in languages such as Arabic which belongs to the Semitic language family. Research in Arabic shows that semantic transparency does not have an effect in the morphological processing of complex words (see Boudelaa & Marslen-Wilson, 2004; Boudelaa & Marslen-Wilson, 2011, 2015; Boudelaa et al., 2010).

The lack of grammatical class effect is consistent with other studies in Persian (Author et al., 2021; Author et al., 2016) and other languages where both nouns and verbs engaged the same brain regions (Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Khader, Scherag, Streb, & Rösler, 2003; Li, Jin, & Tan, 2004; Siri et al., 2008; Vigliocco et al., 2006). We offer three explanations for this finding. The first explanation is that the semantic properties of both compound types in this study were similar. Both compound types consisted of a noun and a verb, only their syntactic properties were different. This finding is in line with studies which have shown controlling semantic properties may help diminish neural dissociation due to grammatical class (Szekely et al., 2005; Lorraine K. Tyler, Russell, Fadili, & Moss, 2001). The second explanation is related to the design we used. We presented all the stimuli out of context in this study. This could mean that the morpho-syntactic properties of the compounds were not accessed during the auditory task. However, this explanation may not be completely feasible because there are studies which have shown differential activation for nouns and verbs even presented as single words out of context (see Thompson et al., 2007). The third explanation posits that the difference between LVCs and NVCs is only a matter of processing time which could only be observed in a behavioural task. However, this explanation was not supported by a masked priming study in Persian and Cantonese (Author et al., 2021). Author et al., (2021) found that both LVCs and NVCs were processed similarly across three different SOAs, although unique interaction patterns emerged in both Persian and Cantonese. It seems that the first explanation is the most viable in this study.

Our findings suggest that transparency effects and morphological operations reported in English and other languages are not universal (see Gunther, Smolka, & Marelli, 2018; Smolka et al., 2019; Smolka, Preller, & Eulitz, 2014). We think that semantic transparency is not a static property of the compound representation, but it is a processing property which could change as a result of peculiar properties of languages and online task/modality related manipulations. Our findings partially support the predictions of meaning construction approaches only at the decomposition phase at least in auditory modality. Future research, however, will be needed with other modalities and different task manipulations.

The ability to combine words and come up with meaningful higher order elements has been extensively studied (Bemis & Pylkkänen, 2011; Friederici, 2020; Hagoort & Indefrey, 2014; Lyu et al., 2019). Although a recent meta-analysis on fMRI studies tries to offer a neural segregation for both syntactic and semantic composition in the brain (Zaccarella, Schell, & Friederici, 2017), we believe it is notoriously difficult to distinguish the neural signature of semantic unification from the syntactic one (Hagoort & Indefrey, 2014) despite using sophisticated and sensitive ways of data analysis such as RSA in our study.

We studied Persian which is a synthetic language with a uniquely productive system in compounding. It is unique because compounding is a relatively common device allowing far more productivity using the same lexical items than is found in other Indo-European languages studied to date. We submit that more cross-linguistic research is needed to test theoretical models that are derived mostly from West European languages. There is a need for more diverse studies on languages with different morphological properties than the few languages which dominate the literature in morphological processing. Finally, we believe that researchers should not shy away from publishing null effects in the field because they could be very useful just like significant effects.

The authors have no conflict of interest to declare.

The data and scripts can be downloaded from the following link from OSF. (Link not included not to reveal the names of the authors).

This experiment was not preregistered.

# References

Aleahmad, A., Amiri, H., Darrudi, E., Rahgozar, M., & Oroumchian, F. (2009). Hamshahri: A standard Persian text collection. *Knowledge-Based Systems, 22*(5), 382-387. doi:10.1016/j.knosys.2009.05.002

Baayen, R. H., Dijkstra, T., & Schreuder, R. (1997). Singulars and plurals in Dutch: Evidence for a parallel dual-route model. *J Mem Lang, 37*(1), 94-117. doi:10.1006/jmla.1997.2509

Bell, M. J., & Schäfer, M. (2016). Modelling semantic transparency. *Morphology, 26*(2), 157-199. doi:10.1007/s11525-016-9286-3

Bemis, D. K., & Pylkkänen, L. (2011). Simple Composition: A Magnetoencephalography Investigation into the Comprehension of Minimal Linguistic Phrases. *The Journal of Neuroscience, 31*(8), 2801-2814. doi:10.1523/jneurosci.5003-10.2011

Bertram, R., Laine, M., Harald Baayen, R., Schreuder, R., & Hyönä, J. (2000). Affixal homonymy triggers full-form storage, even with inflected words, even in a morphologically rich language. *Cognition, 74*(2), B13-25. doi:10.1016/s0010-0277(99)00068-2

Boudelaa, S., & Marslen-Wilson, W. D. (2004). Allomorphic variation in Arabic: implications for lexical processing and representation. *Brain Lang, 90*(1-3), 106-116. doi:10.1016/s0093-934x(03)00424-3

Boudelaa, S., & Marslen-Wilson, W. D. (2011). Productivity and priming: Morphemic decomposition in Arabic. *Language and Cognitive Processes, 26*(4-6), 624-652. doi:10.1080/01690965.2010.521022

Boudelaa, S., & Marslen-Wilson, W. D. (2015). Structure, form, and meaning in the mental lexicon: evidence from Arabic. *Language, Cognition and Neuroscience, 30*(8), 955-992. doi:10.1080/23273798.2015.1048258

Boudelaa, S., Pulvermuller, F., Hauk, O., Shtyrov, Y., & Marslen-Wilson, W. (2010). Arabic morphology in the neural language system. *J Cogn Neurosci, 22*(5), 998-1010. doi:10.1162/jocn.2009.21273

Bozic, M., Fonteneau, E., Su, L., & Marslen-Wilson, W. D. (2015). Grammatical analysis as a distributed neurobiological function. *Hum Brain Mapp, 36*(3), 1190-1201. doi:10.1002/hbm.22696

Bozic, M., Marslen-Wilson, W. D., Stamatakis, E. A., Davis, M. H., & Tyler, L. K. (2007). Differentiating morphology, form, and meaning: neural correlates of morphological complexity. *J Cogn Neurosci, 19*(9), 1464-1475. doi:10.1162/jocn.2007.19.9.1464

Bozic, M., Tyler, L. K., Ives, D. T., Randall, B., & Marslen-Wilson, W. D. (2010). Bihemispheric foundations for human speech comprehension. *Proc Natl Acad Sci U S A, 107*(40), 17439-17444. doi:10.1073/pnas.1000531107

Brooks, T. L., & Cid De Garcia, D. (2015). Evidence for morphological composition in compound words using MEG. *Frontiers in Human Neuroscience, 9*. doi:10.3389/fnhum.2015.00215

Butterworth, B. (1983). Lexical representation. In B. Butterworth (Ed.), *Language production* (pp. 257–294). New York: Academic Press.

Bybee, J. (1995). Regular morphology and the lexicon. *Language and Cognitive Processes, 10*(5), 425-455. doi:10.1080/01690969508407111

Carota, F., Bozic, M., & Marslen-Wilson, W. (2016). Decompositional Representation of Morphological Complexity: Multivariate fMRI Evidence from Italian. *J Cogn Neurosci, 28*(12), 1878-1896. doi:10.1162/jocn_a_01009

Duñabeitia, J. A., Laka, I., Perea, M., & Carreiras, M. (2009). Is Milkman a superhero like Batman? Constituent morphological priming in compound words. *European Journal of Cognitive Psychology, 21*(4), 615-640. doi:10.1080/09541440802079835

El-Bialy, R., Gagné, C. L., & Spalding, T. L. (2013). Processing of English compounds is sensitive to the constituents&#8217; semantic transparency. *The Mental Lexicon, 8*(1), 75-95. doi:10.1075/ml.8.1.04elb

Eulitz, C., & Smolka, E. (2017). *The brain differentiates between known and unknown word compositions but not between transparent and opaque meaning composition: ERP-evidence from the processing of German nominal compounds and pseudo-compounds*. Paper presented at the the annual meeting of the society for the neurobiology of language (SNL), Baltimore, Maryland, USA.

Family, N. (2014). *Semantic Spaces of Persian Light Verbs: A Constructionist Account*: Brill Academic Pub.

Friederici, A. D. (2020). Hierarchy processing in human neurobiology: how specific is it? *Philosophical Transactions of the Royal Society B: Biological Sciences, 375*(1789), 20180391. doi:doi:10.1098/rstb.2018.0391

Frisson, S., Niswander-Klement, E., & Pollatsek, A. (2008). The role of semantic transparency in the processing of English compound words. *British Journal of Psychology, 99*(1), 87-107. doi:doi:10.1348/000712607X181304

Gagné, C. L., & Spalding, T. L. (2004). Effect of relation availability on the interpretation and access of familiar noun–noun compounds. *Brain and Language, 90*(1), 478-486. doi:https://doi.org/10.1016/S0093-934X(03)00459-0

Gagné, C. L., & Spalding, T. L. (2009). Constituent integration during the processing of compound words: Does it involve the use of relational structures? *J Mem Lang, 60*(1), 20-35. doi:10.1016/j.jml.2008.07.003

Gaskell, M. G., & Marslen-Wilson, W. D. (1997). Integrating Form and Meaning: A Distributed Model of Speech Perception. *Language and Cognitive Processes, 12*(5-6), 613-656. doi:10.1080/016909697386646

Giraudo, H., & Grainger, J. (2001). Priming complex words: Evidence for supralexical representation of morphology. *Psychon Bull Rev, 8*(1), 127-131. doi:10.3758/bf03196148

Gunther, F., Smolka, E., & Marelli, M. (2018). 'Understanding' differs between English and German: Capturing systematic language differences of complex words. *Cortex*. doi:10.1016/j.cortex.2018.09.007

Hagoort, P., & Indefrey, P. (2014). The Neurobiology of Language Beyond Single Words. *Annual Review of Neuroscience, 37*(1), 347-362. doi:10.1146/annurev-neuro-071013-013847

Hay, J., & Baayen, H. (2002). Parsing and productivity. In G. Booij & J. Van Marle (Eds.), *Yearbook of Morphology 2001* (pp. 203-235). Dordrecht: Springer Netherlands.

Hernandez, A. E., Dapretto, M., Mazziotta, J., & Bookheimer, S. (2001). Language switching and language representation in Spanish-English bilinguals: an fMRI study. *Neuroimage, 14*(2), 510-520. doi:10.1006/nimg.2001.0810

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nat Rev Neurosci, 8*(5), 393-402. doi:10.1038/nrn2113

Hunston, S. (2002). *Corpora in Applied Linguistics*. Cambridge: Cambridge University Press.

Inhoff, A. W., Radach, R., & Heller, D. (2000). Complex Compounds in German: Interword Spaces Facilitate Segmentation but Hinder Assignment of Meaning. *J Mem Lang, 42*(1), 23-50. doi:https://doi.org/10.1006/jmla.1999.2666

Jackendoff, R., & Wittenberg, E. (2014). What You Can Say Without Syntax: A Hierarchy of Grammatical Complexity. In F. Newmeyer & L. Preston (Eds.), *Measuring Linguistic Complexity*. Oxford: Oxford University Press.

Ji, H., Gagné, C. L., & Spalding, T. L. (2011). Benefits and costs of lexical decomposition and semantic integration during the processing of transparent and opaque English compounds. *J Mem Lang, 65*(4), 406-430. doi:10.1016/j.jml.2011.07.003

Juhasz, B. J. (2018). Experience with compound words influences their processing: An eye movement investigation with English compound words. *Quarterly Journal of Experimental Psychology, 71*(1), 103-112. doi:10.1080/17470218.2016.1253756

Khader, P., Scherag, A., Streb, J., & Rösler, F. (2003). Differences between noun and verb processing in a minimal phrase context: a semantic priming study using event-related brain potentials. *Cognitive Brain Research, 17*(2), 293-313. doi:10.1016/s0926-6410(03)00130-7

Kim, S. Y., Yap, M. J., & Goh, W. D. (2018). The role of semantic transparency in visual word recognition of compound words: A megastudy approach. *Behavior Research Methods*. doi:10.3758/s13428-018-1143-3

Klimovich-Gray, A., & Bozic, M. (2019). Domain-general and domain-specific computations in single word processing. *Neuroimage*, 116112. doi:https://doi.org/10.1016/j.neuroimage.2019.116112

Klimovich-Gray, A., Tyler, L. K., Randall, B., Kocagoncu, E., Devereux, B., & Marslen-Wilson, W. D. (2018). Balancing prediction and sensory input in speech comprehension: The spatiotemporal dynamics of word-recognition in context. *The Journal of Neuroscience*. doi:10.1523/jneurosci.3573-17.2018

Koester, D., & Schiller, N. O. (2008). Morphological priming in overt language production: electrophysiological evidence from Dutch. *Neuroimage, 42*(4), 1622-1630. doi:10.1016/j.neuroimage.2008.06.043

Koester, D., & Schiller, N. O. (2011). The functional neuroanatomy of morphology in language production. *Neuroimage, 55*(2), 732-741. doi:https://doi.org/10.1016/j.neuroimage.2010.11.044

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine, 15*(2), 155-163. doi:https://doi.org/10.1016/j.jcm.2016.02.012

Kriegeskorte, N., Mur, M., & Bandettini, P. (2008). Representational similarity analysis - connecting the branches of systems neuroscience. *Frontiers in Systems Neuroscience, 2*(4). doi:10.3389/neuro.06.004.2008

Leminen, A., Smolka, E., Duñabeitia, J. A., & Pliatsikas, C. (2018). Morphological processing in the brain: The good (inflection), the bad (derivation) and the ugly (compounding). *Cortex*. doi:https://doi.org/10.1016/j.cortex.2018.08.016

Li, P., Jin, Z., & Tan, L. H. (2004). Neural representations of nouns and verbs in Chinese: an fMRI study. *Neuroimage, 21*(4), 1533-1541. doi:10.1016/j.neuroimage.2003.10.044

Libben, G., Derwing, B. L., & de Almeida, R. G. (1999). Ambiguous Novel Compounds and Models of Morphological Parsing. *Brain and Language, 68*(1), 378-386. doi:https://doi.org/10.1006/brln.1999.2093

Libben, G., Gagné, C. L., & Dressler, W. U. (2020). The representation and processing of compounds words. In (pp. 336-352): DE GRUYTER MOUTON.

Lyu, B., Choi, H. S., Marslen-Wilson, W. D., Clarke, A., Randall, B., & Tyler, L. K. (2019). Neural dynamics of semantic composition. *Proceedings of the National Academy of Sciences, 116*(42), 21318-21327. doi:10.1073/pnas.1903402116

MacGregor, L. J., & Shtyrov, Y. (2013). Multiple routes for compound word processing in the brain: Evidence from EEG(). *Brain and Language, 126*(2), 217-229. doi:10.1016/j.bandl.2013.04.002

Marslen-Wilson, W., & Tyler, L. K. (1980). The temporal structure of spoken language understanding. *Cognition, 8*(1), 1-71. doi:10.1016/0010-0277(80)90015-3

Marslen-Wilson, W., Tyler, L. K., Waksler, R., & Older, L. (1994). Morphology and meaning in the English mental lexicon. *Psychol Rev, 101*(1), 3-33. doi:10.1037/0033-295X.101.1.3

Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word-recognition. *Cognition, 25*(1), 71-102. doi:https://doi.org/10.1016/0010-0277(87)90005-9

Marslen-Wilson WD, Bozic. M., Tyler LK. (2014). Morphological systems in their neurobiological contexts. In G. M (Ed.), *The Cognitive Neurosciences* (5 ed.). Cambridge, MA: MIT Press.

McKinnon, R., Allen, M., & Osterhout, L. (2003). Morphological decomposition involving non-productive morphemes: ERP evidence. *Neuroreport, 14*(6), 883-886. doi:10.1097/00001756-200305060-00022

Nili, H., Wingfield, C., Walther, A., Su, L., Marslen-Wilson, W., & Kriegeskorte, N. (2014). A toolbox for representational similarity analysis. *PLoS Comput Biol, 10*(4), e1003553. doi:10.1371/journal.pcbi.1003553

Perrachione, T., & Ghosh, S. (2013). Optimized Design and Analysis of Sparse-Sampling fMRI Experiments. *Frontiers in Neuroscience, 7*(55). doi:10.3389/fnins.2013.00055

Pollatsek, A., & Hyönä, J. (2005). The role of semantic transparency in the processing of Finnish compound words. *Language and Cognitive Processes, 20*(1-2), 261-290. doi:10.1080/01690960444000098

Sandra, D. (1990). On the representation and processing of compound words: Automatic access to constituent morphemes does not occur. *The Quarterly Journal of Experimental Psychology Section A, 42*(3), 529-567. doi:10.1080/14640749008401236

Schell, M., Zaccarella, E., & Friederici, A. D. (2017). Differential cortical contribution of syntax and semantics: An fMRI study on two-word phrasal processing. *Cortex, 96*(Supplement C), 105-120. doi:https://doi.org/10.1016/j.cortex.2017.09.002

Schreuder, R., & Baayen, R. H. (1997). How Complex Simplex Words Can Be. *J Mem Lang, 37*(1), 118-139. doi:https://doi.org/10.1006/jmla.1997.2510

Siri, S., Tettamanti, M., Cappa, S. F., Della Rosa, P., Saccuman, C., Scifo, P., & Vigliocco, G. (2008). The neural substrate of naming events: effects of processing demands but not of grammatical class. *Cerebral Cortex, 18*(1), 171-177.

Smolka, E., & Libben, G. (2017). 'Can you wash off the hogwash?' – semantic transparency of first and second constituents in the processing of German compounds. *Language, Cognition and Neuroscience, 32*(4), 514-531. doi:10.1080/23273798.2016.1256492

Smolka, E., Libben, G., & Dressler, W. U. (2019). When morphological structure overrides meaning: evidence from German prefix and particle verbs. *Language, Cognition and Neuroscience, 34*(5), 599-614. doi:10.1080/23273798.2018.1552006

Smolka, E., Preller, K. H., & Eulitz, C. (2014). 'Verstehen' ('understand') primes 'stehen' ('stand'): Morphological structure overrides semantic compositionality in the lexical representation of German complex verbs. *J Mem Lang, 72*, 16-36. doi:10.1016/j.jml.2013.12.002

Szekely, A., D'Amico, S., Devescovi, A., Federmeier, K., Herron, D., Iyer, G., . . . Bates, E. (2005). Timed action and object naming. *Cortex, 41*(1), 7-25.

Taft, M. (2004). Morphological Decomposition and the Reverse Base Frequency Effect. *The Quarterly Journal of Experimental Psychology Section A, 57*(4), 745-765. doi:10.1080/02724980343000477

Taft, M., & Forster, K. I. (1976). Lexical storage and retrieval of polymorphemic and polysyllabic words. *Journal of Verbal Learning and Verbal Behavior, 15*(6), 607-620. doi:https://doi.org/10.1016/0022-5371(76)90054-2

Thompson, C. K., Bonakdarpour, B., Fix, S. C., Blumenfeld, H. K., Parrish, T. B., Gitelman, D. R., & Mesulam, M.-M. (2007). Neural Correlates of Verb Argument Structure Processing. *J Cogn Neurosci, 19*(11), 1753-1767. doi:10.1162/jocn.2007.19.11.1753

Tyler, L. K., & Marslen-Wilson, W. (2008). Fronto-temporal brain systems supporting spoken language comprehension. *Philos Trans R Soc Lond B Biol Sci, 363*(1493), 1037-1054. doi:10.1098/rstb.2007.2158

Tyler, L. K., Russell, R., Fadili, J., & Moss, H. E. (2001). The neural representation of nouns and verbs: PET studies. *Brain, 124*(8), 1619-1634. doi:10.1093/brain/124.8.1619

Uppenkamp, S., Johnsrude, I. S., Norris, D., Marslen-Wilson, W., & Patterson, R. D. (2006). Locating the initial stages of speech-sound processing in human temporal cortex. *Neuroimage, 31*(3), 1284-1296. doi:10.1016/j.neuroimage.2006.01.004

Vigliocco, G., Warren, J., Siri, S., Arciuli, J., Scott, S., & Wise, R. (2006). The role of semantics and grammatical class in the neural representation of words. *Cerebral Cortex, 16*(12), 1790-1796. doi:10.1093/cercor/bhj115

Walther, A., Nili, H., Ejaz, N., Alink, A., Kriegeskorte, N., & Diedrichsen, J. (2016). Reliability of dissimilarity measures for multi-voxel pattern analysis. *Neuroimage, 137*(Supplement C), 188-200. doi:https://doi.org/10.1016/j.neuroimage.2015.12.012

Yang, Y. H., Marslen-Wilson, W. D., & Bozic, M. (2017). Syntactic Complexity and Frequency in the Neurocognitive Language System. *J Cogn Neurosci, 29*(9), 1605-1620. doi:10.1162/jocn_a_01137

Zaccarella, E., Meyer, L., Makuuchi, M., & Friederici, A. D. (2017). Building by Syntax: The Neural Basis of Minimal Linguistic Structures. *Cerebral Cortex, 27*(1), 411-421. doi:10.1093/cercor/bhv234

Zaccarella, E., Schell, M., & Friederici, A. D. (2017). Reviewing the functional basis of the syntactic Merge mechanism for language: A coordinate-based activation likelihood estimation meta-analysis. *Neuroscience & Biobehavioral Reviews, 80*, 646-656. doi:https://doi.org/10.1016/j.neubiorev.2017.06.011

Zou, L., Packard, J. L., Xia, Z., Liu, Y., & Shu, H. (2016). Neural Correlates of Morphological Processing: Evidence from Chinese. *Frontiers in Human Neuroscience, 9*(714). doi:10.3389/fnhum.2015.00714

Zwitserlood, P. (1989). The locus of the effects of sentential-semantic context in spoken-word processing. *Cognition, 32*(1), 25-64. doi:https://doi.org/10.1016/0010-0277(89)90013-9

Zwitserlood, P. (1994). The role of semantic transparency in the processing and representation of Dutch compounds. *Language and Cognitive Processes, 9*(3), 341-368. doi:10.1080/01690969408402123

Figure 1

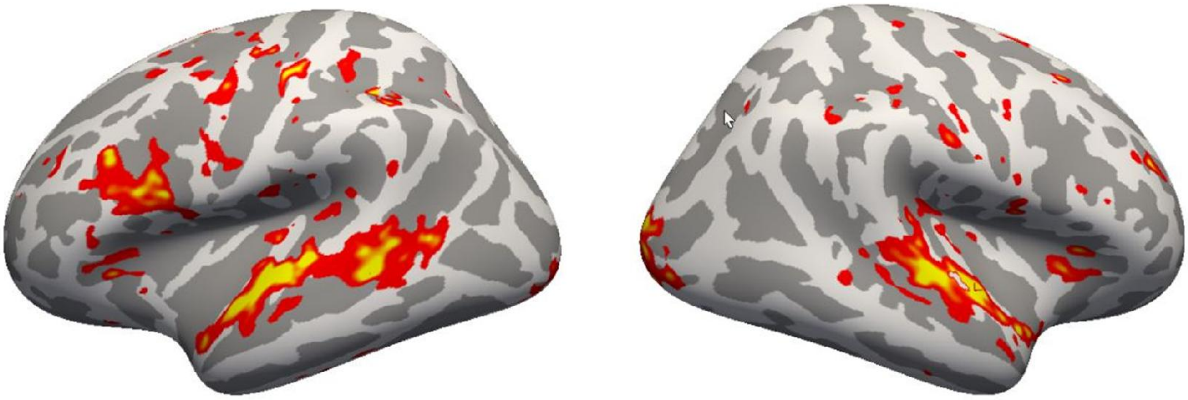

Figure 2