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Original
Consistency measures individuate dissociating semantic modulations in priming paradigms: A new look on semantics in the processing of (complex) words / Amenta, S.; Crepaldi, D.; Marelli, M.. - In: QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY. - ISSN 1747-0226. - 73:10(2020), pp. 1546-1563. [10.1177/1747021820927663]

Availability:
This version is available at: 20.500.11767/110844 since: 2020-11-10T17:46:35Z

Publisher:

Published
DOI:10.1177/1747021820927663

Consistency measures individuate dissociating semantic modulations in priming paradigms: A new look on semantics in the processing of (complex) words

Running header: Consistency measures in priming paradigms

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Abstract

In human language the mapping between form and meaning is arbitrary, as there is no direct connection between words and the objects that they represent. However, within a given language, it is possible to recognize systematic associations that support productivity and comprehension. In this work, we focus on the consistency between orthographic forms and meaning, and we investigate how the cognitive system may exploit it to process words. We take morphology as our case study, since it arguably represents one of the most notable examples of systematicity in form-meaning mapping. In a series of three experiments, we investigate the impact of form-meaning mapping in word processing by testing new consistency metrics as predictors of priming magnitude in primed lexical decision. In Experiment 1, we re-analyse data from five masked morphological priming studies and show that Orthography-Semantics-Consistency explains independent variance in priming magnitude, suggesting that word semantics is accessed already at early stages of word processing and that crucially semantic access is constrained by word orthography. In Experiment 2 and 3, we investigate whether this pattern is replicated when looking at semantic priming. In Experiment 2, we show that Orthography-Semantics-Consistency is not a viable predictor of priming magnitude with longer SOA. However, in Experiment 3, we develop a new semantic consistency measure based on the semantic density of target neighbourhoods. This measure is shown to significantly predict independent variance in semantic priming effect. Overall our results indicate that consistency measures provide crucial information for the understanding of word processing. Specifically, the dissociation between measures and priming paradigms shows that different priming conditions are associated with the activation of different semantic cohorts.

Consistency measures individuate dissociating semantic modulations in priming paradigms: A new look on semantics in the processing of (complex) words

Introduction: the relevance of form-meaning mapping for word processing

It is rather uncontroversial that human language is a *symbolic* system in the sense that, generally speaking, words' form is arbitrarily associated to meaning in the external or psychological world, e.g., there is nothing in the sound of the words 'table' or 'love' that links to the four–legs object on which we can put things or that special affection that we feel for our closest (e.g., Hockett, 1963; Saussure, 1916). Nevertheless, actual lexicons (and linguistic experience more in general; e.g., Louwerse and Connell, 2011; Monaghan, Christiansen and Fitneva, 2011) are full of non–arbitrary associations between form and meaning (e.g., Louwerse and Qu, 2017), possibly as the result of learning constraints in the cultural evolution of languages, which may have introduced some systematicity in an in–principle random domain (e.g., Kirby, Cornish and Smith, 2008). Whether our cognitive system captures these associations and use them to inform language processing is an unsettled issue, and a potentially revealing one in terms of the cognitive machinery that supports human language.

A clear example of non–arbitrary association between form and meaning is lexical morphology. Morphemes have been described (e.g., Bloomfield, 1933) as units of form (i.e., clusters of sounds) associated to a certain meaning (a sememe), or, more recently (Hocket, 1958) as the smallest individually meaningful elements in the utterances of a language (for a current view on morphemes, see Blevins, 2016). For example, the suffix -*ness* in, e.g., *concreteness, emptiness* and *kindness* is indicative of an nominal form, while the prefix *un-* typically conveys a meaning of negation, lacking or *the opposite of*, as in, e.g., *unhappy*, *unpack*, or *unfairness*. These associations are not always perfectly systematic—a *dealer*, a *farmer* and a *baker* are all people who *deal*, *farm* and *bake*, but *-er* has a very different meaning in *darker* and no meaning at all in *corner*. Furthermore, if it is true that a *singer* is someone who *sings*, a *cooker* is something that a person uses to *cook*, so even in similar syntactic contexts (*sing* and *cook* are both verbs) the same suffix can play a very different role (e.g., agentive vs. instrumental). However, although probabilistic in nature, there is indeed information about meaning in the form of a word when morphology is involved. When interested in studying the mapping between form and meaning, morphology is thus a perfect test case.

Scholars have been investigating for years whether morphemes have a psychological reality, which results in morphological representations being involved in the processing of morphologically complex words[1]. Particularly for what concerns visual word identification and reading, there is now little doubt that morphological information has an impact on cognitive processing (i.e., morphological information is extracted during the processing of complex words). A number of morphological effects have been established very clearly over the years (see Amenta and Crepaldi, 2012, for a comprehensive review), most notably morphological priming (e.g., Feldman, 2000; Longtin, Segui, and Hallé, 2003; Rastle, Davis, and New, 2004; Longtin and Meunier, 2005, Rueckl and Aicher, 2008).

Morphological priming effects are mainly reported in masked priming lexical decision experiments, where stem targets (e.g., deal) preceded by morphologically complex prime words (e.g., dealer) are recognized faster than when they are preceded by an unrelated word (e.g. poetry). Notably, morphologically related prime-target pairs, yield larger facilitation than orthographically related pairs (e.g., scandal-scan), indicating that the observed priming effect comes from the morphological structure of the prime word rather than from the simple orthographic similarity between prime and target.

[1] It should be noted here that there is a principle distinction between morphology as a linguistic description and morphology as an assumption for cognitive investigation. One can state that something described in morphological terms has an impact on processing without necessarily implying that that very something is represented in the cognitive system. Indeed, processing can lead to effects that mimic morphology on the basis of different, more general level processes (Marelli, Traficante and Burani, in press).

This effect has been shown to emerge even when the prime is not fully parsable or when the form–to–meaning correspondence is less clear–cut than in the standard examples described above. For example, McCormick, Rastle and Davis (2008) reported consistent masked priming in words where the perfect concatenation of well-defined chunks of letters (deal+er, glass+y, kind+ness) is lost. In pairs like *adorable–adore*, the *e* of the stem *adore* is missing in the derived form *adorable*. In *lover-love*, the letter *e* is shared between the stem *love* and the derivational suffix *–er*. In *dropper-drop* the derivational process provokes the duplication of the final consonant of the stem. In all these cases, McCormick and colleagues (2008) were able to find standard morphological priming. These results point to a flexible process that is able to overcome orthographic variations (albeit predictable, to some extent) in establishing form-meaning correspondences. Convergent results come from a similar study in Italian, a language that do not present free-stems, therefore, where it is in principle impossible to have a perfect segmentation of stem and affix given the presence of thematic vowels in all simple/base forms, e.g., *banchiere* - *banca*, where the root is *banc-* and *-a* is the thematic vowel identifying grammatical gender and number (see Marelli, Amenta, Morone and Crepaldi, 2013, Experiment 1). In this experiment, the authors replicated the morphological priming effect for morphological (e.g., *banchiere – banca*; banker - bank) and pseudo-morphological (e.g., *ostaggio-oste*; hostage - host) pairs, similar to the one reported in the studies on English discussed above.

More strikingly, investigating the morphological decomposition of irregular inflected words, again in masked priming conditions, Crepaldi, Rastle, Coltheart and Nickels (2010) reported that verb irregular past forms (e.g., *shook*) were able to prime their base form (i.e., *shake*), more than an orthographic control (e.g., *shock*) or another unrelated prime (e.g., *touch*). In these words, the simple concatenative view that nicely fit regular morphology (i.e., where two distinct morphemes are put together for form a new lexical item, e.g., *dealer* = *deal* + *er*) is just inapplicable and, although form similarity pairs with semantic relatedness, there is no way to predict exactly the form of one morphological relative from another member of the family (the past tense form of *shake* could well be *shaked*, as in *fake–faked*, or *shade*, as in *make–made*, or really anything else, in principle). Form–

to–meaning correspondence is thus far from being entirely regular; and yet, the morphological effect remains. The authors also showed that this effect cannot be simply traced back to orthographic regularities, since no priming effect was found for pairs of unrelated words that maintained the same pattern alternation, e.g., *look-lake*. These results ideally complement effects described for morphological family size in unprimed lexical decision, showing that morphological relations have an impact in word processing irrespective of surface overlap (De Jong, Schreuder and Baayen, 2000).

Even more extreme, it has been shown that morphological priming emerges also when semantic relationships are completely lost, and words only maintain the surface appearance of morphological complexity. That is, morphological priming emerges in genuinely related words such as *dealer–deal*, but also in morphologically–structured, but otherwise completely unrelated words, such as *corner–corn* (e.g., Longtin et al., 2003; Rastle et al., 2004; but see Feldman O'Connor and del Prado Martín, 2009, and Milin, Feldman, Ramscar, Hendrix and Baayen, 2017). This pattern of results cannot come but from the fact that a word–ending *-er* brings morphological information very often in the language experience of an English speaker. Therefore, apparently, the cognitive system not only notices this, but also develops such a strong processing strategy based on this information that it is also applied to counterexamples such as *corner* (Marelli and Baroni, 2015).

It is rather clear that these results do not fit easily with a classic morphological approach based on very well defined representational units (the morphemes), which are combined according to precise patterns (combinatorial rules) (see, e.g., Baayen, Milin, Đurđević, Hendrix, and Marelli, 2011). Morphological relationships might instead be described as a special case of a more general form–to–meaning mapping pattern (Marelli et al., in press), where some very systematic/predictable instances (e.g., dealer–deal, kindness–kind) live together with a very wide set of more graded, probabilistic patterns (e.g., *fell–fall*, *thought–think*; or, outside the domain of concatenative morphology strictly defined, *glow–glare–gloom–gleam–glimmer*, an example of the so called phonaestemes, Bloomfield, 1933; Bergen, 2004; Pastizzo and Feldman, 2009; or *'attack–att'ack, p'ermit–perm'it*, where stress flags grammatical class in homophones, Sherman, 1975).

Taken altogether these results suggest that the exploration of the mapping between orthographic forms and their associated meaning is one of the most relevant questions that we need to address and to which we must find an answer if we really want to understand how readers are able to access meanings starting from strings of arbitrary symbols.

Orthography-Semantics consistency

Very much in line with this approach, we proposed a few years ago a new metric for form-meaning mapping, which we called Orthography–to–Semantics Consistency (OSC; Marelli, Amenta and Crepaldi, 2015). OSC quantifies the degree of semantic relatedness between a (target) word and the members of its orthographic family (named orthographic relatives), defined by all the words that embed the target word. The target string is always a whole word (regardless of its morphological complexity or its class). We define as orthographic relative of the target, all the words in the lexicon that contain the exact same orthographic sequence independently from its position (e.g., orthographic relatives of *corn* are words like *cornfield*, *corner*, *popcorn*, *Cornish*, *Cornwall*, *cornstarch*, *corny*, *unicorn*, *scorn, scornful*, etc.) and regardless of the relationship between the relative and the target (i.e., relatives are not necessarily morphologically or semantically related to the target, as seen in the examples above). For example, the string *widow* is contained in, e.g., *widower, widowed*, and *widowhood*, therefore all these words will be considered orthographic relatives of "widow" (for more details on how the orthographic relatives are defined and validation of this procedure, see Marelli and Amenta, 2018). Because all these words are associated to the meaning of WIDOW, OSC will be high (that is, the semantic similarity between the target – *widow* in this case - and all its neighbours is high). Essentially, this high value of OSC reflects the fact that every time one encounters the string *widow* in the English lexicon, they can be quite sure that the meaning WIDOW will be involved. In other words, one has reliable information on meaning, based on form. On the other hand, the orthographic family of the string *whisk* includes words such as *whisky, whiskey, whisker,* and *whiskered*, most of which are not associated to the meaning WHISK. In this case, OSC will thus be low—not much information on meaning is available, based on form. If you will, *whisk* is not a "reliable" cue to its meaning.

Formally, OSC is the frequency–weighted[2] semantic similarity between the semantic representation of a word (generated using methods from distributional semantics, similar to LSA; see below for details) and the semantic representations of its orthographic relatives (see Marelli et al., 2015 and Marelli and Amenta, 2018 for details on this method):

$$OSC(t) = \frac{\sum_{i=1}^{k} cos\left(\vec{t}, \vec{r_i}\right) * f_{r_i}}{\sum_{i=1}^{k} f_{r_i}}$$

where t is the target word, r_i each of its k orthographic relatives, and f_{ri} the corresponding frequencies.

We showed that OSC explains unique variance in word identification times (unprimed lexical decision data taken from the British Lexicon Project, Keuleers, Lacey, Rastle and Brysbaert, 2012). Words that present higher degrees of consistency between their meanings and those of their orthographic relatives (i.e., high OSC) are easier to recognize, whereas words with less consistency between their meaning and those of their orthographic relatives (i.e., low OSC values) are harder to recognize. It does seem, then, that the visual identification system is sensitive to how consistent is the mapping between orthographic form and meaning (Marelli et al., 2015; Marelli and Amenta, 2018).

This result opens a series of interesting questions on lexical access and the role that morphology has in it. In fact, morphology is the most prominent example of form-meaning mapping, and, as discussed in the previous section, there is a rich psycholinguistic literature concerning its role in word processing (e.g., Amenta and Crepaldi, 2012).

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[2] In fact, it is known that vector representations for low-frequency words are typically low-quality (especially in such a large corpus as the one considered here), and hence cosine measures applied to them are often unreliable. Weighting the individual cosine contributions to the OSC estimates by their frequency permits to minimize the noise brought by these elements (see Amenta & Marelli, 2018).

What is important to note here is, however, that a consistency measure like OSC is not strictly speaking a morphological measure, since the selection of orthographic relatives for each word is not based on morphological family, but is defined purely on orthographic basis. In other words, OSC allows us to explore the role of form-meaning mapping in word recognition, going beyond the morphological description. However, since OSC is based on a string's orthographic relatives, and since this pool of words includes potentially morphological relatives, which are typically used as primes in morphological priming experiments, OSC has obvious implications on this latter too, an issue that we left unaddressed in Marelli et al. (2015). In fact, the OSC formula provides itself a straightforward prediction relative to the impact that OSC might have in modulating morphological priming magnitude. OSC represents the activation of a semantic network informed by orthography. As a results, in a masked morphological priming paradigm, the prime will have a different impact on the target depending on the activated network (that is, the target OSC).

Moreover, OSC is a frequency weighted metric, that is, the contribution of each orthographic relative to the final value is proportional to its frequency. To take the previous example, the orthographic family of the word *corn* will be composed of words like *corner*, *cornstarch*, *popcorn*, *cornfield*, *unicorn*, *scornful* etc. The contribution that each relative will give to the estimate of OSC is determined by its frequency, so that words with lower frequency will have less impact in the determination of the mapping between the string *corn* and the meaning CORN. Therefore, we can predict that the impact of the prime will depend on the interplay between its frequency and the semantic network activated by the target orthography. A frequency modulation is expected from the target too, as the target is itself part of the orthographic–semantic family—if it has high frequency, it will "dominate" the cohort just as well as the primes, possibly leaving less room for OSC to exert its influence on priming. Starting from these considerations, we can hypothesize that priming magnitude should be modulated by the interaction between target OSC and prime word frequency, as well as the interaction between target OSC and target frequency. We tested these hypotheses in Experiment 1 using data from five morphological masked priming studies.

A second goal in Experiment 1 was to see how much of the effect that is typically attributed to overt experimental manipulations in typical masked priming studies (transparent vs. opaque vs. orthographic) can actually be explained by a different between-set priming sensitivity related to the OSC of the targets. In fact, Marelli et al. (2015) found that OSC tends to be higher in transparent morphological conditions, and this may be so pretty much by design—items in opaque conditions must have at least one semantically inconsistent members in the orthographic family (the prime), while this may not be the case for most words that are selected as part of the transparent condition. So it may be the case that differences in the priming effect magnitude in the different conditions might be related to the different distribution of OSC. In other words, we tested if in morphological processing literature priming conditions were "confounded" with OSC and if OSC had an impact on morphological priming.

Experiment 1: OSC in masked priming

Materials and methods

We investigated the impact of OSC on priming effect, as observed in the test set from five studies from the morphological processing literature using masked priming (Rastle, Davis, Marslen-Wilson and Tyler, 2000; Rastle et al., 2004; Marslen-Wilson, Bozic and Randall, 2008; Dipendaele, Sandra and Grainger, 2005; Andrews and Lo, 2013)[3]. OSC estimates were obtained as described in Marelli et al. (2015). As reference corpus we considered a concatenation of the ukWaC (http://wacky.sslmit.unibo.it/), English Wikipedia (http://en.wikipedia.org/), and the British National Corpus (BNC) (http://www.natcorp.ox.ac.uk/) corpora (about 2.8 billion words in total), lemmatized

[3] We included datasets from these experiments based on the following reasons: (i) they all included English items in a between-target design; (ii) they all focused on the derivation process with suffixed words; (iii) they all presented comparable SOAs ; and (iv) the authors kindly shared their data with us.

and PoS-tagged[4] using Maltparser (Nivre, Hall, Nillson, 2006; Nivre, Hall, Nillson, Chanev, Eryigit, Kübler, ... and Marsi, 2007). A semantic space was obtained using the following parameter settings: 5-word co-occurrence window; Positive Pointwise Mutual Information (Church & Hanks, 1990); Non-negative Matrix Factorization (Arora, Ge, and Moitra, 2012) with 350 dimensions. OSC was computed as the frequency-weighted average of the cosine proximity (based on the semantic space just described) between the target vector and each of its orthographic relatives. These latter were defined as any words embedding the target (differently from the original 2015 paper, we did not include an onset-specific positional constraint in the selection of relatives, as we observed that it leads to a worse measure performance; see Marelli and Amenta, 2018).

For each target, priming effect magnitude (PEM) was computed as the difference between the RTs in the unrelated condition (explorer-deal) and the RTs in the corresponding related condition (dealer-deal). This measure was computed for the related prime-unrelated prime-target sets included in both the five studies considered and our semantic space, for a total of 645 datapoints across 366 unique targets (as the same target could be included in different datasets, possibly with different primes). Each set could belong to one of four condition (as determined in the original studies from where the item sets were taken): transparent (where prime and target are morphologically and semantically related; e.g., dealer-deal), semi-transparent (where prime and target are pseudo-morphologically related, while their semantic relation is not direct; e.g., archer-arch), opaque (where prime and target are pseudo-morphologically related and semantically unrelated; e.g., corner-corn), orthographic (where the prime is a morphologically simple word which embeds the target as orthographic substring; e.g., scandal-scan). To guarantee comparability with the original studies, we left each item assigned to the category where it belonged in the original paper. Priming effect magnitude can be considered an estimate of how much the related prime positively contributes to the

[4] Lemmatization and Part-of-Speech (PoS) tagging are two standard steps in the automatic pre-processing of corpora. The first consists in reducing all inflected forms to their lemma; the second, consists in discriminating words on the basis of their part of speech (hence we will have separate representations for "run" as verb and "run" as noun).

target recognition. Note that the interpretation of priming results in terms of facilitation vis-à-vis inhibition must be always considered in the context of the adopted baseline. Given the design of the considered studies, any observed facilitation is to be intended with respect to a context where the target is preceded by an unrelated word. The distribution of priming effect magnitude is represented in Figure 1, along with its association with the OSC measure.

*** Insert Figure 1 about here ***

Priming effect magnitude was used as dependent variable. In a first analysis, we explored the relation between OSC and priming conditions. We also compared the impact of OSC and priming condition in explaining priming magnitude by relying on AIC and BIC metrics (to evaluate the fit of our models, see Wagenmakers and Farrel, 2004), as well as testing the unique contribution of OSC over and above the experimental condition. In a second analysis, the effects of interests were the interactions between OSC and prime frequency, and between OSC and target frequency (as both target and prime are in principle part of the semantic cohort of orthographic relatives captured through OSC). Moreover, family size (i.e., the type count of morphologically complex words related to a given base word; Schreuder and Baayen, 1997), OLD20 (i.e., average Levenshtein distance between the 20 most frequent orthographic neighbours of a given word; Yarkoni, Balota, and Yap, 2008), and orthographic length were included as covariates in the analysis, as well as random intercepts for prime, target and source dataset (Baayen, Davidson and Bates, 2008). Frequency values were extracted from SUBTLEX-UK (Van Heuven, Mandera, Keuleers and Brysbaert, 2015), and family size was computed on the basis of CELEX annotation (Baayen, Piepenbrock and Gulikers, 1995). Both measures were log-transformed. OLD20 was obtained from Balota, Yap, Hutchinsons, and Cortese (2007). Table 1 reports a correlation matrix including the considered predictors.

*** Insert Table 1 about here ***

We started from an initial model including the interactions of interest along with these covariates, that was progressively simplified by removing effects that did not contribute to the model fit. Once the best-fitting model was identified, a model-criticism (Baayen et al., 2008) procedure was applied to identify and remove outlying datapoints (on the basis of 2 SD of standardized residuals) in order to exclude their potential impact. Results of the resulting refitted model are reported. In all analyses we applied mixed-effects models (Baayen et al., 2008) with by-target random intercepts. Models were estimated using the R packages lme4 (Bates, Sarkar, Bates, and Matrix, 2007) and lmerTest (Kuznetsova, Brockhoff and Christensen, 2015).

Results

In Marelli et al. (2015), OSC was found to be higher in transparent vis-à-vis opaque morphological conditions. As shown by Figure 2, this is also the case in the present study (see also Jared, Jouravlev, and Joanisse, 2017): the larger the degree of transparency of the pair, the higher the OSC value ($F[3,12.24]=51.48$; $p=.0001$).

*** Insert Figure 2 about here ***

*** Insert Table 2 about here ***

The impact of both OSC and priming condition in explaining priming magnitude was tested against a baseline including family size, length, OLD20, target frequency, prime frequency, and random intercepts for primes, targets pairs and source studies. Details of the baseline model are reported in Table 2 (variance components: random intercept for the targets 449.4; residual variance

2941.9). We then fitted two separate models, one with OSC as main predictor and one with "condition" as main predictor. Both variables significantly predict priming magnitude over and above this baseline (OSC effect: $F[1,292.29]=27.46$, $p=.0001$; condition effect: $F[3,308.67]=5.83$, $p=.0007$). However, the inclusion of OSC leads to a better fit (AIC=7052, BIC=7092) than the inclusion of condition (AIC=7066, BIC=7115). Moreover, OSC is able to explain significant variance in the residuals of the condition model ($F[1;643.05]=8.95$, $p=.0029$), while condition fails to account for any significant variance in the residuals of the OSC model ($F[3;641.08]=2.01$, $p=.1104$) . This indicates that target OSC explains variance in morphological priming that is not captured by traditional experimental manipulations (i.e., condition), whereas the opposite does not seem to be the case.

Note that this does not trivially depend on OSC capturing, by chance, a continuous characterization of semantic transparency: when we continuously model semantic transparency as the degree of relatedness between stem and derived form, using the currently best-performing data-driven semantic estimates (Mandera, Keuleers, and Brysbaert 2017), we observe a smaller effect ($F[1;295.07]=8.02$; $p=.0049$) and a worse fit to masked-priming data (AIC = 7071, BIC = 7111) than the one observed for OSC.

Of course, this does not indicate that OSC, per se, can fully capture morphological priming. The priming phenomenon necessarily reflects the interplay between two elements, a prime and a target, and here OSC characterizes only the target. Rather, OSC may reflect the priming pattern because it identifies an aspect of the target that makes it particularly sensitive to the prime property. Indeed, as anticipated in the Introduction, the very way OSC is defined predicts an interaction between OSC and prime frequency, along with an interaction between OSC and target frequency. We tested these predictions in a second analysis. Results are reported in Table 3[5] (variance components: random intercept for the targets 209.5; residual variance 2041.9).

[5] Family size, target length, OLD20, and experimental conditions were removed from the model because they did not contribute significantly to the model fit. However, the same results hold when including these as covariates.

*** Insert Table 3 about here ***

OSC interacts significantly with both target frequency and prime frequency. The interaction between OSC and target frequency is illustrated in Figure 3: the smaller the OSC, the less the impact of target frequency on priming magnitude.

*** Insert Figure 3 about here ***

The interaction between OSC and prime frequency is represented instead in Figure 4. The higher the prime frequency, the larger its impact on the priming effect. However, the nature of the prime frequency effect changes with target OSC: when this latter is small, having high-frequency prime leads to a smaller priming effect; conversely, when OSC is high, high-frequency primes yield larger effects.

*** Insert Figure 4 about here ***

Discussion

In this first experiment we analysed the impact of OSC on masked morphological priming. We first explored the relationship between OSC and the traditional experimental conditions described in the masked priming studies. We showed that OSC is significantly different in the four experimental condition used in those studies, that is, OSC and conditions are confounded, at least in these sets of items. In particular, OSC is highest in the transparent condition and lowest in the orthographic condition, with opaque and semi–opaque items standing between the two extremes. We thus tested the impact of OSC against the traditional variable "condition" in determining the priming effect magnitude and we showed that the former seems to be a better predictor of priming effect than the latter. OSC explains more variance than "condition" and, more importantly, is able to account for variance that is left over by condition, while the reverse is not true (i.e., condition does not explain variability that is left over by OSC).

These data show that there is a second possible account of the classic pattern observed in masked morphological priming experiments. This alternative account does not build on a strong divide between separate classes of prime items (e.g., transparent vs. opaque vs. orthographic), but relies on consistency in the form–to–meaning mapping with a continuous, graded metric (OSC), determining a different sensitivity to priming effect in different targets. More importantly, this metric is not based exclusively on the primes and the targets used in the experiment, but reflects the way these primes and targets are semantically and orthographically entangled across the whole lexicon. The focus is thus moved from the mere prime–target relationship to the network where primes and targets belong, that is, their relationship with other words based on both form and meaning (thus including potential morphological relatives). These dynamics stress the importance of probabilistic form–to–meaning associations that are created through language and reading experience.

As a further validation of OSC as a critical construct in lexical dynamics, we showed that, as expected by the very definition of the metric, OSC impact on priming interacts with prime and target frequency. As for the latter, the critical factor is that a target is always part of the relative pool considered to compute its OSC—a word is always embedded in itself, and is thus part of the potential semantic network activated by its orthography. With this in mind, the interpretation of the OSC by target frequency interaction is rather straightforward: very frequent targets dominate the semantic cohort they activate through orthography; hence they will leave less room for other representations in the network to influence the lexical dynamics. As a result, the effect of OSC is mostly evident when target frequency is relatively low: when the target meaning does not dominate the activated network, and this latter is semantically consistent (roughly corresponding with traditionally defined transparent and -to a certain extent- opaque conditions), processing is more likely to be sensitive to priming manipulation.

The interaction goes in the opposite direction when it comes to prime frequency—OSC effect is stronger when the prime is more frequent. This makes perfect sense: whereas a dominant (that is, high frequency) target in the neighbourhood leaves no room for the prime to exert its influence, a dominant (that is, high frequency) prime allows the priming effect to show up in all its strength, pending a high OSC level. However, there is also another way to look at the interaction, which provides a revealing qualification of the dynamics captured by OSC: prime frequency is positively correlated with priming in high–OSC targets, but negatively correlated with priming in low–OSC targets. That is to say, in highly consistent families, a frequent prime is a blessing, because form is a reliable cue to meaning and thus primes do yield exploitable information on the target; thus, the stronger the prime, the easier target processing. When form to meaning mapping is instead quite inconsistent in the family, a frequent prime hinders target identification, as form is not a reliable cue to meaning and thus primes are not likely to yield information on the target.

At this point, it is necessary to discuss – briefly – the difference between OSC and morphological family size. The two constructs, in fact, may appear similar at first glance, and indeed, they are both attempts at capturing the distribution of orthographic and semantic features of words. However they differ in many respects. Morphological family size (Schreuder and Baayen, 1997) has been defined as a measure of the number of words in the lexicon that are related to the same base word. Therefore, not only morphological relatives (words that share the same stem), but also simple orthographic relatives contribute to the computation of OSC (words that embed the same string, independently from the role that that string has in the structure of the word). At the same time, while morphological family size would take into account variations of morphologically related words (*fell* will be counted in the morphological family of *fall,* and *gedachte* will be part of the morphological family of the verb *denken*), OSC would not (De Jong, Schreuder and Baayen, 2000). Importantly, it is worth noting here that while family size is a count measure, OSC does not merely take into account the number of relatives, rather it captures how semantically close they are to the representation of the target word. Moreover, family size is based on type frequency, hence capturing an element of word productivity, while, to compute OSC, the frequency of each relative is used to weight the contribution of its vector representation, so that the most frequent relative will contribute more to OSC[6]. Interestingly, De Jong et al. (2000) show that the effect of morphological family size is strictly a type count effect and it is independent from token frequency effects (like surface frequency, base frequency, cumulative root frequency, and, especially family frequency). In other words, the role of frequency and the type of frequency used in the computations of OSC and family size sets the two measures apart: while the focus of family size is on morphological productivity, the focus of OSC is on the semantic consistency of the orthographic family of a word. Adding to this, OSC and morphological family size are only marginally correlated (Marelli and Amenta, 2018). Taken altogether, these considerations suggest that OSC and morphological family size capture qualitatively different latent variables.

In conclusion, the results of Experiment 1 provide a validation of the theoretical insight behind OSC. We showed that the pattern of the morphological priming effect, typically observed in the literature, can be explained in the more general terms of orthography-semantics mapping. Words with higher OSC belong to orthographic families that are also semantically consistent; according to our prediction, in these networks frequent words, when used as primes, exert the maximum effect on the target word.

These data indicate clearly that semantic relationships between prime and target are relevant in masked priming. Of course, it is now necessary to understand which "type" of semantics is in place in this type of task. Based on how OSC is computed, the semantic network at play is principally activated by the target orthography. Since we know that masked priming paradigm focuses the word

[6] On the practical side it also worth noting that, in the present work, OSC is based on better disambiguated data than family size: OSC was induced from a lemmatized, PoS-tagged corpus, whereas family size was not. This latter procedure is suboptimal, since family members from different lexeme-ancestors can give rise to opposite effects on reaction times, with congruent family members affording facilitation and incongruent ones inhibition (Moscoso del Prado Martin, Deutsch, Frost, Schreuder, de Jong, & Baayen, 2005). Note, however, that the low correlation between OSC and family size is observed even when the former is computed on a non-preprocessed corpus (Marelli & Amenta, 2018)

recognition system on peripheral features[7] (e.g., Tzur and Frost, 2007), it may be the case that the OSC effects on priming are specific to masked conditions and do not extend to other paradigms. Moreover, it is also known that (pseudo) morphological prime-target sets (e.g., dealer-deal; corner-corn) manifest pure semantic effects in overt priming paradigms[8] (e.g., Rueckl and Aicher, 2008). In other words, when the prime is explicitly perceivable, the only effect that emerges is the one for transparent pairs (i.e., *dealer* facilitates *deal*, but *corner* yields no effect on *corn*), which translates in a pure semantic priming pattern. For this reasons, it is possible that the pattern that we observed in the present experiment is driven by specific conditions that make orthographic features more relevant in our data. As we argued above, in a masked morphological priming paradigm, both the short prime exposure and the prime-target relationship seem to give to orthography a "leading role". However, we can hypothesize that, (i) in long-soa conditions, and (ii) in a scenario where orthographic similarity has little to no role, we might not be able to observe the same pattern of effects, making the OSC effect specifically informative of the semantic modulation occurring in masked morphological priming, rather than in priming paradigms in general.

Experiment 2: OSC in semantic priming

To provide a control for these considerations, in a second experiment, we test the impact of OSC on priming in unmasked conditions. To this end, we tested OSC on the same targets used in Experiment 1, but this time on semantic, rather than morphological masked priming. Because OSC captures dynamics in the mapping between the orthographic and the semantic space, whereas

[7] Note, however, that even masked priming effects can be modulated by task requirements (Duñabeitia, Kinoshita, Carreiras and Norris 2011; Marelli et al., 2013), list composition (Feldman and Basnight-Brown, 2008), and can sometimes capture semantic information (e.g., Bottini et al., 2016).

[8] This pattern is typically found in English. Studies on German, for example, have shown that purely morphological effects are observed when applying long-term priming paradigms (Smolka, Preller and Eulitz, 2014).

semantic priming is determined primarily by the semantic space alone, the prediction is that the OSC effects shown in Experiment 1 should fade away, or at least shrink substantially.

Material and methods

Of the 366 target stems that we considered in Experiment 1, we selected those 124 that were also available in the Semantic Priming Project (SPP, Hutchison, Balota, Neely, Cortese, Cohen-Shikora, Tse, ... and Buchanan, 2013). The SPP contains lexical decision latencies from 768 subjects to 1,661 targets preceded by either a semantically associated prime or an unrelated prime (SOA is 200 ms). For each target, we selected its corresponding associated primes and unrelated primes as defined in the SPP, and we took their mean RTs. The total dataset included 247 related prime-unrelated prime -target sets (since, in the SPP, each target could be presented with different primes; e.g. *bake* could be preceded by *broil* or *cake* as associated primes and by *station* or *south* as unrelated primes).

Priming magnitude was then calculated by subtracting RTs in the unrelated vs. related condition.

Once we have obtained PEM as a dependent variable, we adopted exactly the same approach described in Experiment 1, with the only exception that we also included in the models the LSA estimate (Landauer and Dumais, 1997) of the association strength between the prime and the target, as reported in the SPP itself, since this is a known critical predictor of semantic priming effect and it had been previously used to validate the semantic priming database.

Results

Results are reported Table 4 (variance components: random intercept for the targets 205.3; residual variance 3223.1). Priming magnitude is only predicted by the degree of semantic relatedness between prime and target, and the frequency of the target (higher frequency targets are associated to smaller priming effects). No impact of OSC can be observed, neither by itself, nor in interaction with prime/target frequency: the corresponding parameters were removed from the model because they did not significantly contribute to its fit (along with length, family size, OLD20, and prime frequency).

*** Insert Table 4 about here ***

Discussion

As expected, we did not observe any effect of OSC, in line with the theoretical definition and mathematical characterization of the measure: we expect priming effect to be carried by the presence of a prime in the cohort activated by a target, and in semantic priming the prime is typically not included in the cohort of meanings captured by OSC. In other words, OSC describes the dynamics of the mapping between the orthographic and semantic spaces, while semantic priming is driven by dynamics within the semantic space alone; thus, OSC is not able to account for semantic priming. The lack of relevant OSC effects in this experiment attests the specificity for masked morphological priming of the results reported in Experiment 1, thus providing further validation to the theoretical construct behind OSC. In fact, OSC captures the relation between the orthographic form of a word and the consistency of the semantic network activated on the basis of it. Therefore, we are able to observe an effect of OSC on priming magnitude only when the relationship between prime and target is based on both orthographic and semantic features. However, if this is the case, a natural prediction is that we can compute a consistency measure that, while not focusing on the orthography-informed cohort of OSC, should be able to capture the priming pattern of semantic priming by focusing only on the semantic relationship between prime and target. Following this prediction, we extend our analysis of semantic consistency in semantic priming data in the next section.

Experiment 3: The Intra-Semantics Consistency

In Experiment 2 we found no effect of OSC in semantic priming, which we attributed to the fact that this metric describes a portion of the semantic network that is not much involved in the experimental paradigm. But what if the same dynamics underlying OSC is indeed applied to the semantic system per se? If truly semantic consistency is a critical factor in the activation of the semantic network, then adopting the same approach to describe the part of the network that is indeed involved in semantic priming should allow us to account for this phenomenon. In what follows, we thus develop a new metric, which we would describe as the OSC counterpart for intra-semantics relations, and assess whether this new metric is indeed able to explain semantic priming.

Material and Methods

For the same targets that we considered in Experiment 2 (n= 124), we computed a measure that parallels OSC, but is focused on semantics only. This measure, which we call Intra-Semantics Consistency (hence, ISC), is the average semantic relatedness between a target and its 20 top semantic neighbours (automatically extracted from a distributional semantic model), weighted by the neighbour frequency. Its mathematical characterization is identical to OSC, as showed by the formula reported below:

$$ISC(t) = \frac{\sum_{i=1}^{k} cos(\vec{t}, \vec{r_i}) * f_{r_i}}{\sum_{i=1}^{k} f_{r_i}}$$

The difference only lies in the selection of the relatives—while for OSC the target neighbourhood was defined orthographically (all the words that embed the target), for ISC it is defined semantically (the 20 closest semantic neighbours)[9]. Examples of words with low ISC in our dataset are *lend* and *sign*; while items with high ISC are, e.g., *train* and *bake*.

We then ran the same analysis described in Experiment 2, but now including ISC in place of OSC. PEM was again computed from the Semantic Priming Project (Hutchison et al., 2013). We now expect ISC to be a significant predictor of priming. Also, symmetrically to OSC in Experiment 1, we expect an interaction between ISC, and prime and target frequency, because ISC describes the structure of the semantic neighbourhood where both the prime and the target sit.

Results

In line with our predictions, ISC affects semantic priming significantly, and interacts with prime frequency in predicting priming magnitude (see Table 5; variance components: random intercept for the targets 43.46; residual variance 3433.64). However, we do not observe the interaction between target frequency and consistency that we found with morphological masked priming in Experiment 1. As for the previous experiments, family size and target length were considered in the analysis, but were not included in the final model, because they did not contribute to the model fit. Conversely, we confirm the impact of prime-target relatedness as gauged by LSA; and also find a main effect of target frequency whereby more frequent targets yield smaller facilitation.

*** Insert Table 5 about here ***

The interaction between prime frequency and ISC is described in Figure 5. In general, ISC modulates priming more substantially with lower prime frequency. From a different perspective, the

[9] In principle, a parallel procedure could be applied to OSC by, for example, choosing as orthographic relatives the top 20 neighbours as defined by Levenshtein distance. However, the performance of such obtained OSC estimates resulted to be subpar (Marelli and Amenta, 2018).

less consistent the semantic network of the target (lower ISC value), the more facilitatory the impact of the prime frequency: the higher the frequency of the prime, the larger the facilitation.

*** Insert Figure 5 about here ***

Discussion

The results largely confirm the predictions that motivated Experiment 3 — just as OSC qualifies masked morphological priming, ISC qualifies semantic priming. That is, the same descriptive tool that seems to characterize effectively the interface between the orthographic and the semantic system is also able to describe the semantic system per se. These data further validate the mathematical formulation behind ISC/OSC as an effective way to describe semantic networks of relations in the mental lexicon.

More specifically, the nature of the interaction between prime frequency and ISC reported in this experiment can be interpreted in terms of potential competition between prime and target. In very dense semantic cohorts (that is, high ISC), the target meaning is potentially confused with its neighbours. Thus, a strong (i.e., high frequency) prime can act as a competitor, counteracting priming. In sparser semantic cohorts (that is, low ISC), target neighbours are less likely to be confounded with the target itself. As a result, strong, high–frequency primes only boost facilitation. Moreover, whereas we observed an interaction between OSC and target frequency in Experiment 1, we fail to observe an interaction between ISC and target frequency here. In Experiment 2, we only find a main effect of target frequency, indicating that the more frequent the target word, the lower the priming effect. An explanation of such a difference may lie on participants' being fully aware of the prime, given the unmasked conditions. In such a scenario, implying a more thorough processing of the prime word, the priming effect would be essentially determined by the prime role in the activated semantic network, while the target saliency would exert inhibition at a more general level.

We should note that ISC is essentially a semantic density measure, as it places a target word at the centre of the semantic network formed by its closest semantic neighbours. In this sense, its effect in a semantic priming paradigm is not unexpected and it is further evidence that target recognition, also in a lexical decision task, is influenced by complex semantic associations (e.g., Jones, Kintsch and Mewhort, 2006; Shaoul and Westbury, 2006). There is indeed wide literature documenting semantic priming effects in word recognition (see Neely, 2012, for a review), and the factors that affect semantic priming have been largely studied for more than 40 years (see McNamara, 2005, for a collection of essays on the topic). Moreover, there is strong evidence that semantic variables, such as semantic richness and semantic density, hold an effect also in the lexical decision task (e.g., Buchanan, Westbury and Burgess, 2001; Pexman, Hargreaves, Siakaluk, Bodner, and Pope 2008; Mirman and Magnusson, 2008; Yap, Tan, Pexman, and Hargreaves, 2011; Yap, Pexman, Wellsby, Hargreaves and Huff, 2012), which, arguably, does not require deep processing of word meaning.

That said, ISC presents some remarkable differences with the semantic variables commonly considered in previous experiments. First of all, although it shares common features with some operationalisations of semantic richness, our measure diverges from this construct under at least one very relevant point: where semantic richness estimates, such as number of features, number of semantic neighbours, number of associates, number of senses and contextual diversity, are notably "count" variables, ISC does not take into consideration the number of relatives for each target in its computation. The difference between ISC and semantic richness is comparable to the difference between OSC and family size that we have discussed in previous sections. A more relevant comparison can be established between ISC and other co-occurrence based measures of semantic density, for example the one proposed by Milin et al. (2017) within the NDL framework, or the Mean Semantic Similarity (hence, MSS; Shaoul & Westbury, 2010, reported by Yap et al, 2011), that was shown to account for response latencies in lexical decision by Yap and colleagues (2011, 2012). In particular, MSS and ISC are both computed as the mean cosine similarity between a target word and its closest *k* neighbours in a high-dimensional semantic space, with the main difference that in the computation of ISC, the similarity with each relative is weighted by the relative's own frequency. In the same way as we did for OSC, this procedure allows for more frequent neighbours to exert greater influence on the final estimate of ISC.

General discussion

The results of our experiments provide further support to the idea that readers are sensitive to the complex structure of the lexical-semantic network, and in particular to the consistency between different parts of this network. Human language is essentially a symbolic system, and therefore there is no intrinsic relationship between form and meaning, and no obvious regularity in the way the basic form units (letters and phonemes) bind together. Despite that, language is full of statistical cues, which the cognitive system could in principle code for making its processing easier and more efficient. The data we present here suggest that this is indeed the case, at least for what concerns the statistical cues that are captured by the mathematics behind OSC and ISC—essentially, consistency metrics.

Morphology fits very well in this framework, as it exactly provides consistency in the way form is organized (letters that are part of the same morphemes occur together more often) and in the way it connects to meaning. Morphology, and particularly the regular, concatenative cases, provides a case of very strong systematicity in this context, and could thus be explained within this framework, which goes well beyond morphology though.

In a first experiment, we tested a prediction that came directly from the formula used to compute OSC, a measure of orthography-semantics mapping. OSC formalizes the frequency weighted semantic similarity between a target word and each of its orthographic relatives, defined as any word in the lexicon that embeds the full target word as sub-string. From this, it follows that, in a masked morphological priming experiment, where primes are morphologically or pseudo-morphologically complex words, and targets are strings embedded in those words, (a) each prime will be also part of the pool of orthographic relatives of its related target; (b) its impact on the priming effect will be modulated by its frequency. We therefore tested the interaction of target OSC and prime frequency on the priming effect magnitude on morphological masked priming data. Results indicate that priming effect magnitude is indeed explained by the interaction of OSC and prime frequency over and above a baseline constituted by length, word frequency and word family size. Given that OSC formalizes orthography – informed semantic activation, we take this result as an indication that, in the masked morphological priming paradigm, the impact of semantics is driven by orthographic information. Interestingly, OSC is not a morphological variable per se; indeed, among the relatives that contribute to target OSC we can also find words that are not morphologically related to the target word itself. Thus, the OSC effect observed here suggests that we should look beyond morphological relationships to explain the pattern of results coming from morphological masked priming data. OSC is a continuous variable describing different degrees of consistency in the mapping between form and meaning, and, in fact, its effect is not limited to prime-target pairs that share a morphological relationship, rather it relates also to pairs that share a simple orthographic relationship. The present data might even suggest that we can read the classical pattern of morphological priming study in a new light: the lack of effect of the orthographic controls (dialogue-dial) is not necessarily dependent on a lack of morphological relationship between prime and target, but can also be explained by the widespread semantic inconsistency of the target orthographic relatives. Conversely, this lack of consistency is not observed in the targets typically employed in the transparent and opaque conditions. In other words, the structure and dynamics of the prime-target lexical-semantic network are more important that the prime-target link itself. Therefore, *dialogue* may fail to prime *dial* not because -*ogue* is not a morpheme, but because the neighbourhood of *dial* in the lexical-semantic network is not really structured, which prevents the extraction of strongly constraining information from the words represented there.

The present results thus suggest a possible reinterpretation of the usual pattern reported in morphological masked priming experiments, that is, transparent pairs yielding similar (or more) priming than opaque pairs, which in turns yield more priming than orthographic pairs. In the morphological processing literature, such conditions co–vary with OSC (Marelli et al., 2015). Here we propose that such a priming pattern can also be interpreted as a continuous and gradual facilitation, modulated by network dynamics in an orthographically-informed semantic space. This explanation is arguably more parsimonious (does not require to assume separate mental categories for different morphological realizations); and also has a stronger explanatory power, as shown in the present study. Moreover, the characterization of OSC as a hybrid variable, formalizing semantic activation on the basis of word orthography, suggests a different perspective on the long-standing debate concerning semantic modulation of morphological effects in masked priming (e.g., Rastle et al., 2004; Feldman et al., 2009; Davis and Rastle, 2010; Feldman, Milin, Cho, Moscoso del Prado Martín, and O'Connor, 2015). In fact, the effect of OSC indicates that asking whether there is a semantic access in masked priming may be a moot question, given the internal dynamics characterizing complex word processing. A better-posed research question would rather ask how semantic access changes in masked-priming context.

We also showed that this account is specific for morphological masked priming paradigm. In fact, we tested the interaction between OSC and prime frequency on the SPP, but could not replicate the results of the first experiment. The absence of an effect in this case was expected. In fact, following the formalization of OSC, its impact should be dependent on the presence of the prime among the target's relatives activated by the target orthographic form. However, in semantic priming, primes and targets are not orthographically related, therefore the prime is not included in the cohort of meanings activated on the basis of the target orthography. It was however possible to compute a consistency measure that is based on the target semantics alone and test its impact on semantic priming. This new analysis was aimed at testing the hypothesis that different priming paradigms could activate different semantic networks. The new measure formalized Intra-Semantic Consistency, ISC, and was computed as the frequency weighted semantic similarity between a word and its semantic neighbours. Following this formalization, semantic priming magnitude should be predicted by an interaction between the frequency of the prime and target ISC (analogously to what happened with OSC and masked morphological priming). The interaction was significant, revealing an interesting pattern connected with semantic density and competition.

Our results suggest that the very same dynamical process can explain priming effect in semantic priming and morphological masked priming. The different pattern of results can be explained only by considering how the semantic network is activated in masked morphological priming paradigm vs. semantic priming paradigm: apparently, different experimental conditions constraint the semantic cohort that is defined by the target, and through which the prime influence can be expressed. In masked priming, the semantic cohort is bound by the orthographic form of the target — masked priming captures form-meaning mapping. In longer-SOA semantic priming, the cohort is activated by purely semantic associations — semantic priming captures meaning-to-meaning mapping. The clear dissociation we observed between OSC and ISC in morphological masked priming vis-à-vis semantic priming is strong evidence in this respect, and permits a better understanding of the prime-target dynamics (and, more specifically, of the role played by prime frequency) in priming experiments.

This pattern is also informative for morphological processing. In fact, it shows that we don't need to assume semantically-blind operations to understand masked morphological priming. Rather, we have to consider more fully the complexity of the semantic network (for a similar claim see Marelli and Baroni, 2015). Given the dissociation with ISC, the pattern of effects in masked priming emerges from the synergy of two components: on the one hand, the limitations imposed by the mask and the short SOA, which limit the amount and depth of processing; on the other hand, the use of morphologically complex words and their stem: item pairs that, by definition, tap into the entanglement of form and meaning that is captured in OSC terms. However, in order to explain the patterns described in the literature we do not need to call for any special status for these words (morphological complexity), nor to assume any ad–hoc operation (e.g., morpho-orthographic segmentation): they may rather be a byproduct of the stimuli employed and the experimental manipulation, which can be explained parsimoniously by looking at patterns between form and meaning.

The different dynamics we observed between the two priming approaches, described here through the interplay between frequency and consistency measures, could be understood in theoretical terms by considering a dissociation between spreading activation and discriminative processes (Schmidtke, van Dyke and Kuperman, 2018). A masked priming condition would lead to shallower processing, guided by the uptake of more peripheral (visual-orthographic) information. In this kind of earlier, pre-decision scenario, similar elements will facilitate each other, and thus easier-to-activate elements (i.e., more frequent primes in more consistent networks) will tend to help more target recognition. On the other hand, long-term semantic priming would take place at a later level, when decision processes take place along with the explicit appreciation of prime-target relations. In this context a discriminative principle may also become important, leading to a more diverse pattern: salient elements (i.e., frequent primes) will generally be helpful in a very dense semantic cohort, but they can end up competing with the target to be recognized, making it more difficult to discriminate, and hindering processing as a result. In this perspective, we may speculate that the difference in the SOA between the two paradigms (35ms vs. 200ms on average) primarily affects the quality of the information affected by the prime-target interplay in the activated semantic network, while processing always involves aspects of word meaning, as it is indicated by the semantic nature of both OSC and ISC.

Although our data and results are specific to morphologically complex words, we believe that our approach has a more general value for the study of word processing as it tackles the importance and opportunity to address the relationship between form and meaning in psycholinguistic research.Models of language processing have long focused on defining words (and language) properties within specific representation layers. Classical cognitive architectures envisaged word processing as a stream of information that flows from an orthographic or phonological input, possibly to a lemma level (a relay for lexical and grammatical information), up to a semantic level where word meanings are represented. This type of modelling assumptions had a direct impact on the empirical work. Most experiments in fact are conducted via factorial contrasts, for example, within a representation layer (e.g. contrasting the processing of abstract vs. concrete words), or by studying one layer against the other (e.g. orthographic vs. semantic). This way of operating is based on the assumption (more or less tacit) that the division between each level or aspect of linguistic description is clear-cut, and, again, while they may influence each other during processing, they are separated and represented in distinct layers within the model. Moreover, even when non-factorial experiments are implemented, typical continuous predictors usually address effects that belong to a specific layer (e.g., concreteness to the semantic layer, or length in letters to the orthographic layer). As a consequence of this "localist" approach, the interface between layers has received poor attention. However, the interface between layers, especially the orthographic and semantic one, is crucial for the understanding of language processing, and the mapping between layers goes beyond the simple information encapsulated within each of them.

The lack of attention gained by the mapping between form and meaning may be mainly due to difficulties in delineating the elements that map onto one another, and to the lack of extensive semantic representation in current models of word processing. In other words, if it is easy to define orthographic units of analysis (may them be letter, bigrams, trigrams, whole words, etc.), without a comprehensive implementation of semantics we miss one extreme of the mapping. However, more recently, the integration of approaches from distributional semantics is allowing to fill this gap in a bottom-up way. Novel proposals, like the one by Marelli and Baroni (2015), Marelli, Gagné and Spalding (2017) and Westbury and Hollis (2019), or novel attempts to shape the semantic "level" of existing models (e.g., Milin, Divjak, and Baayen, 2017; Milin et al., 2017; Baayen, Chuang and Blevins, 2018) give us the possibility to study the connection between form and meaning. And, based on this methodology is in principle possible to build metrics that allow to connect orthographically defined units to distributed semantic representations. As a measure, OSC places itself within this perspective, providing an easy and efficient tool to investigate the impact of form-meaning relationships in word processing (Marelli and Amenta, 2018).

Despite the theoretical considerations that are brought about by OSC and that we have tried to highlight above, it is worth noting that OSC is not a model of word processing itself, but rather an experimental phenomenon that needs to be explained by theoretical proposals and their computational implementations, hence serving for model adjudication. Certainly, the spirit of OSC, with its focus on how orthographic information can be mapped onto diverse semantic representations, fits well with models that build on learning systems and see lexical effects as an epiphenomenon of stable statistical patterns between forms and meanings (Baayen et al., 2011; Baayen, Chuang, Shafaei-Bajestan, & Blevins, 2019; Milin et al., 2017; Seidenberg, 1995; Harm and Seidenberg, 2004). Indeed, connectionist models (or models that exploited connectionist architectures more in general), addressed directly the issue of mapping between different representational nodes. In the revised version of the Harm and Seidenberg's triangle model (2004), orthography and phonology map directly on semantics, highlighting the fact that regularities within the ortho-semantic path pertain mostly to the linguistic morphology. In this model, semantics emerges as a pattern of activations over a set of semantic units that receive information from both the ortho-semantic and the phono-semantic pathway. More recently, a similar architecture was presented (Baayen et al., 2019) assuming vector representations for forms that are mapped linearly onto vector representations for meanings and vice-versa; such a system does not require explicit representations for morphemes or phonemes, but can nevertheless simulate word-processing effects in these domains. Related to these perspectives, the NDL model also offers insights into the mapping between form and meaning as statistical patterns that emerge over word distributions (Milin et al., 2017). We may expect the OSC effect to naturally emerge from these architectures. However, this does not imply that it is impossible for localist models to explain the pattern of effects reported in this paper. In fact, models featuring a lemma level (such as those illustrated in Xu & Taft, 2015, or Crepaldi et al., 2010), and particularly those explicitly positing competition between lemmas (Taft & Nguyen–Hoan, 2010), would have a plausible mechanisms to explain an OSC effect. Lemmas typically sit between form and meaning representations, and thus are well suited to describe the dynamics that are so well quantified by OSC. When a stem inhabits an inconsistent part of the lexical–semantic space (i.e., when it features in words with different meaning, thus having low OSC), it will activate multiple lemmas, which would then compete with each other. This would slow down visual word identification (Marelli et al., 2015) and reduce the priming effect (the present paper). Similarly, the interaction between OSC and prime/target frequency may be explained in terms of frequency–weighted activation in the localist nodes (see above in the Discussion of Experiment 1). There are many details that remain to be uncovered about the cognitive mechanisms that generate the OSC/ISC effect, and both localist and distributed approaches could in principle help to shed lights on them.

Conclusions

In this work, we explored whether the cognitive system exploits consistency in the mapping between form and meaning, and whether these dynamics can be captured by the particular formulation of consistency proposed by Marelli et al. (2015), that is, Orthography–Semantics Consistency (OSC). While addressing these questions, we also developed a new, similarly inspired metric that applies to the semantic network itself, rather than to the mapping between form and meaning; we dubbed this new metric ISC (Intra–Semantics Consistency), and show that it is able to account for semantic priming data taken from the Semantic Priming Project (Hutchison et al., 2013). More generally, we observed that priming data depend heavily on the semantic network activated on the basis of the specifics of the paradigm (e.g., the type of relationship between primes and target, the SOA, the task to be carried out on the target). In particular, we observed that semantic activation is mediated in masked priming by the target word orthography. Conversely, in semantic priming the activation is dominated by the target semantic neighbours. Our results point to a new conception of the priming paradigm whereby the specific relationship between any given prime and any given target must be considered in the context of the lexical–semantic network where those prime and target sit.

The present results add a further piece of evidence for the impact of form-to-meaning consistencies in word recognition. However, OSC itself should not be taken as a comprehensive formulation of how the processing of such consistency is implemented in the cognitive system; rather, it constitutes a measure capturing specific cases of such a nuanced phenomenon by means of corpus data. This is evident when looking at the orthographic relatives considered in the computation of OSC, which do not include strings that are embedded in the target (e.g., *hat* is not taken as a relative of *chat*; Bowers Davis and Hanley, 2005) or words that are semantically related to the target through sublexical strings (e.g., phonaestemes: *glimmer* is not considered a relative of *glitter*; Bergen, 2004; Pastizzo and Feldman, 2009). There is room for improvement in the definition of the OSC measure (see Marelli and Amenta, 2018). However, the fact that an effect can be observed even when applying such a coarse and unrefined measure speaks for the central role of form-meaning mapping in word recognition.

Acknowledgments

Authors' contributions for this paper are as follow: SA, MM and DC conceived the study; SA and MM developed the OSC and ISC measures; MM developed the semantic model and analyzed the data, with contribution from SA; SA, MM and DC drafted the paper. The authors would like to thank Kathy Rastle, William Marslen-Wilson, Kevin Diependaele, Sally Andrews, and their co-authors for having contributed to this work by sharing their data.

Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

Funding

This work was supported by the Fonds Wetenschappelijk Onderzoek – Vlaanderen (FWO) [grant number FWO.OPR.2017.0014.01, project number G011617N]; and a European Research Council Starting Grant 2015 [grant number 679010].

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Table 1. Correlation matrix of the considered predictors.

	OSC	Length	FS	OLD20	Frequency	Prime Freq
OSC	1.00	.345	.129	.271	.188	-.330
Length		1.00	-.152	.702	-.155	-.141
FS			1.00	-.246	.506	.085
OLD20				1.00	-.245	-.140
Frequency					1.00	.159
Prime Freq						1.00

Table 2. Results of the baseline model

	Estimate	Standard Error	dof	t-value	p-value
Intercept	37.84	22.35	331.6	1.69	.0914
Length	-1.55	4.24	325.4	-0.37	.7150
Family Size	-3.03	3.04	296.5	-0.99	.3197
OLD20	14.80	10.68	302.1	1.39	.1669
Frequency	-1.24	1.74	340.7	-0.71	.4772
Prime Frequency	-2.79	1.35	349.7	-2.07	.0389

Table 3. Results of Experiment 1

	Estimate	Std. Error	df	t value	p value
(Intercept)	9.35	21.10	422.6	0.44	.6579
Frequency	2.36	2.29	432.5	1.03	.3025
Prime frequency	-3.34	1.99	354.6	-1.68	.0938
OSC	71.51	33.31	395.7	2.15	.0325
Freq*OSC	-11.65	3.81	385.2	-3.06	.0024
Prime freq*OSC	8.53	3.62	344.7	2.36	.0191

Table 4. Results of Experiment 2

	Estimate	Std. Error	df	t value	p value
(Intercept)	58.489	25.377	128.93	2.305	.0228
Frequency	-6.038	2.617	118.21	-2.307	.0228
Semantic rel. (LSA)	59.024	18.495	229.18	3.191	.0016

Table 5. Results of Experiment 3

	Estimate	Std. Error	df	t value	p value
(Intercept)	-199.728	116.836	212.400	-1.709	0.0888
ISC	369.399	158.054	217.910	2.337	0.0203
Prime frequency	28.917	14.429	218.960	2.004	0.0462
Frequency	-6.739	2.642	124.050	-2.551	0.0119
Semantic rel. (LSA)	55.712	19.111	228.700	2.915	0.0039
ISC*Prime freq.	-40.543	19.922	223.200	-2.035	0.0430

Figure Captions

Figure 1. Distribution of Priming Effect vis-à-vis OSC in the considered morphological masked priming studies.

Figure 2. OSC distribution in the four experimental conditions considered.

Figure 3. Interaction between OSC and target frequency in predicting Priming Effect Magnitude in masked priming. The impact of target frequency is represented through different regression lines, each associated with a different level of OSC. Distributions of target frequency and Priming Effect Magnitude are also reported on the corresponding axes.

Figure 4. Interaction between OSC and prime frequency in predicting Priming Effect Magnitude in masked priming. The impact of prime frequency is represented through different regression lines, each associated with a different level of OSC. Distributions of prime frequency and Priming Effect Magnitude are also reported on the corresponding axes.

Figure 5. Interaction between ISC and prime frequency in predicting Priming Effect Magnitude in semantic priming. The impact of prime frequency is represented through different regression lines, each associated with a different level of ISC. Distributions of prime frequency and Priming Effect Magnitude are also reported on the corresponding axes.

Figure 1

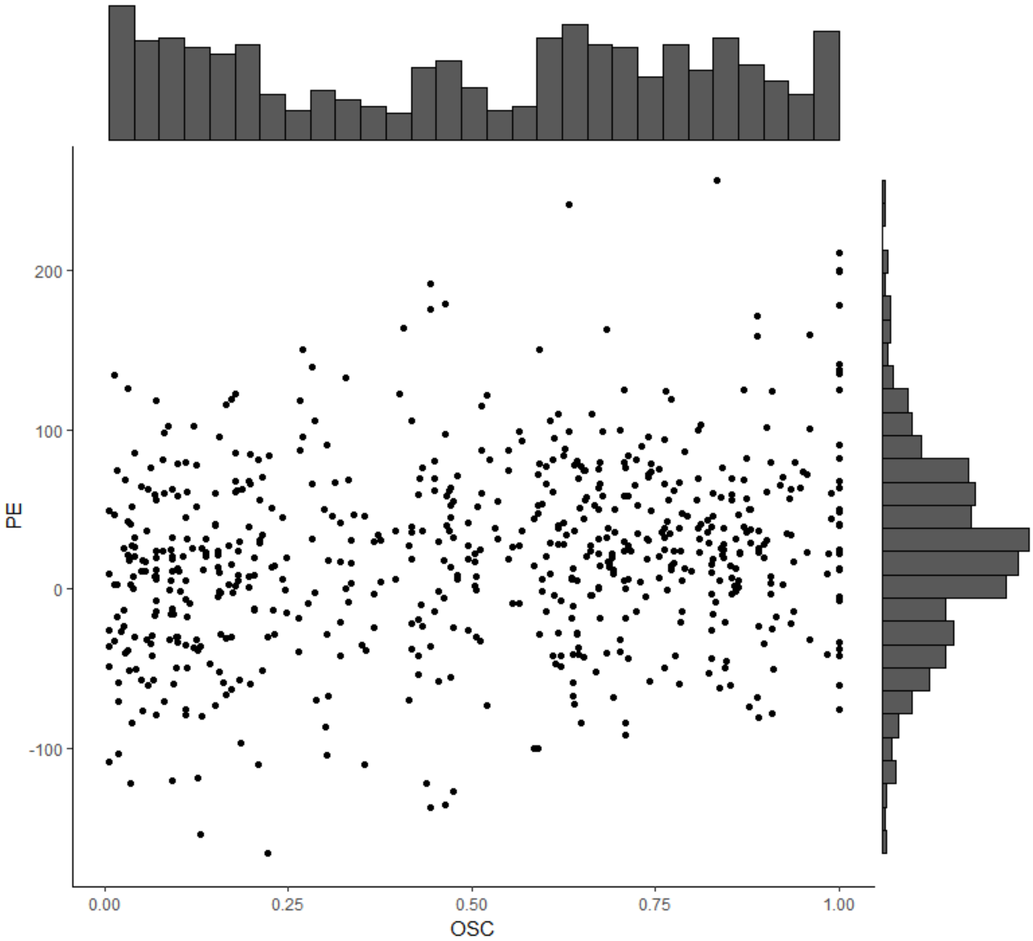


Figure 2

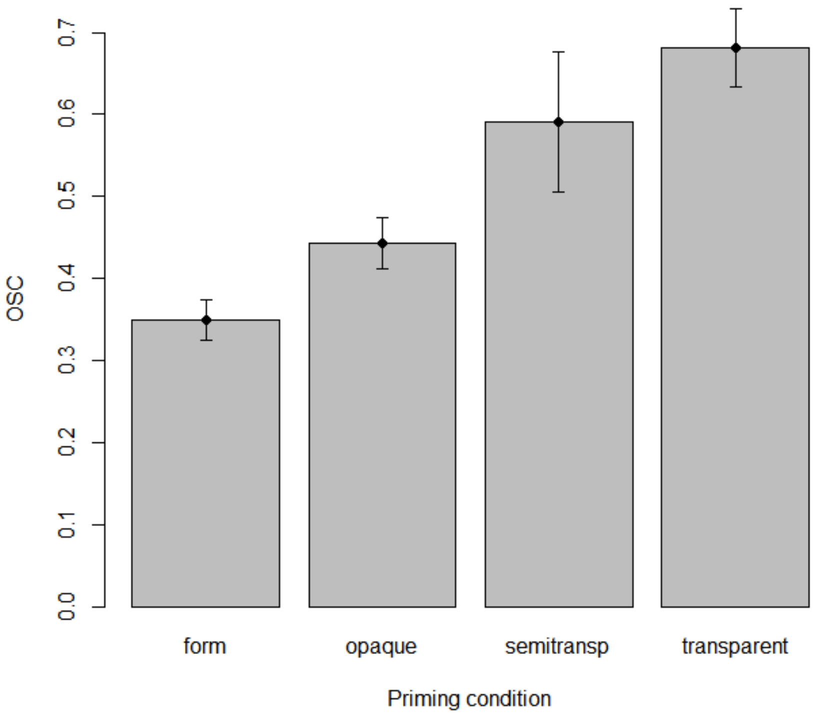


Figure 3

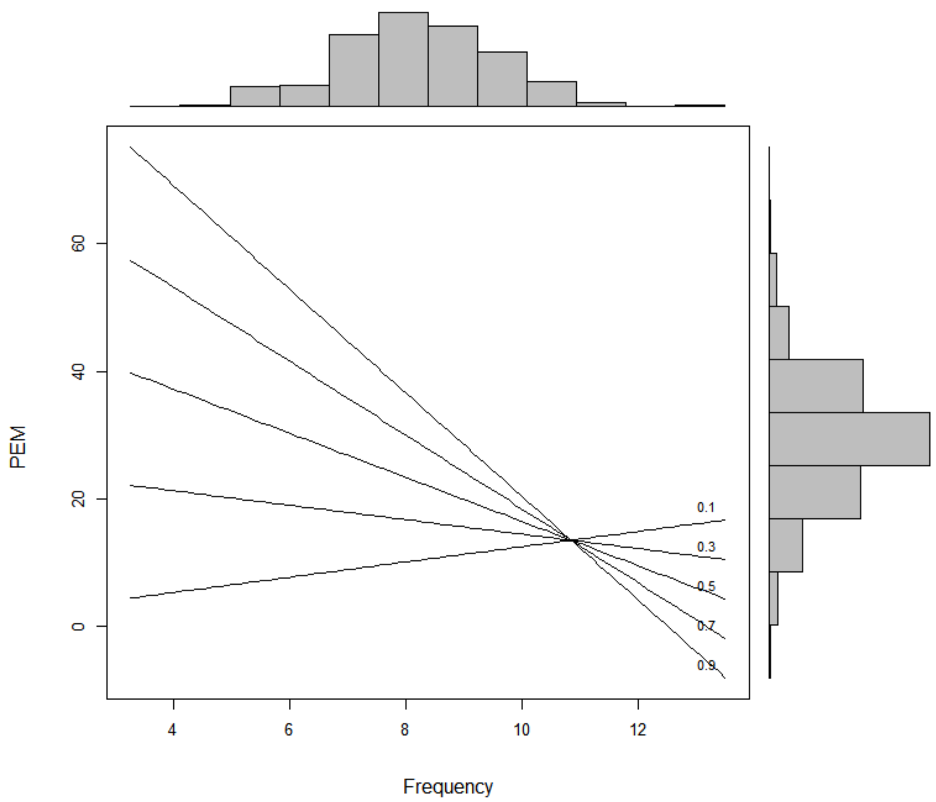


Figure 4

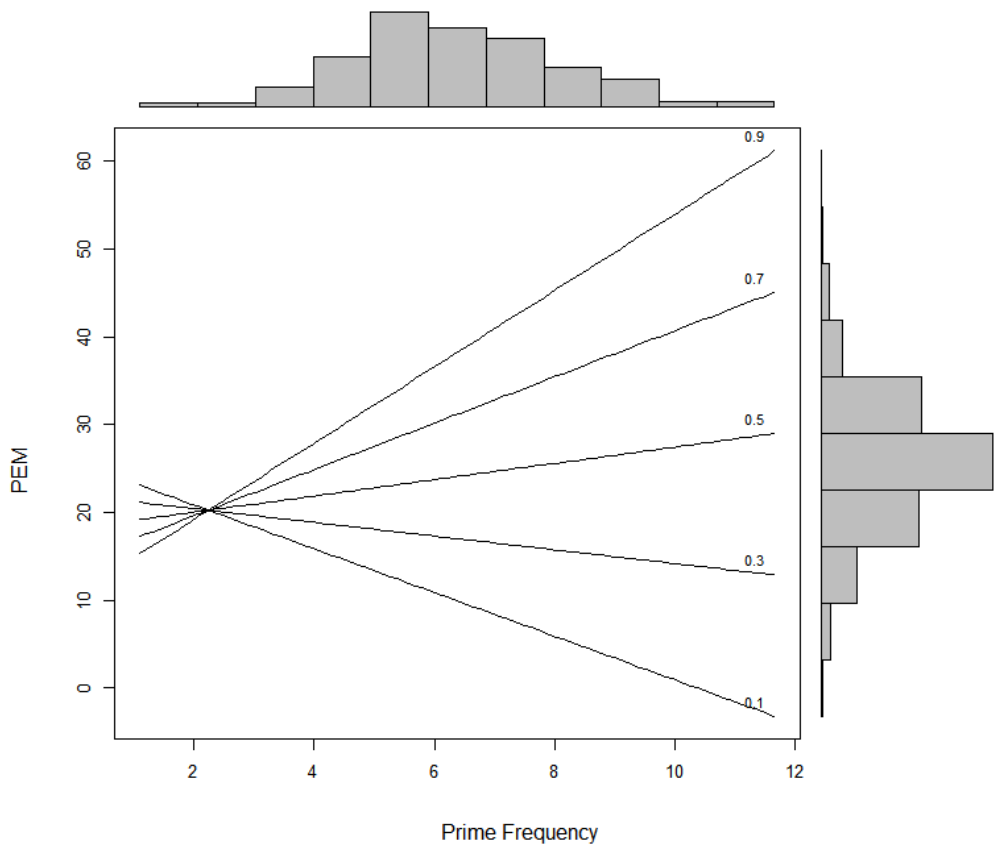
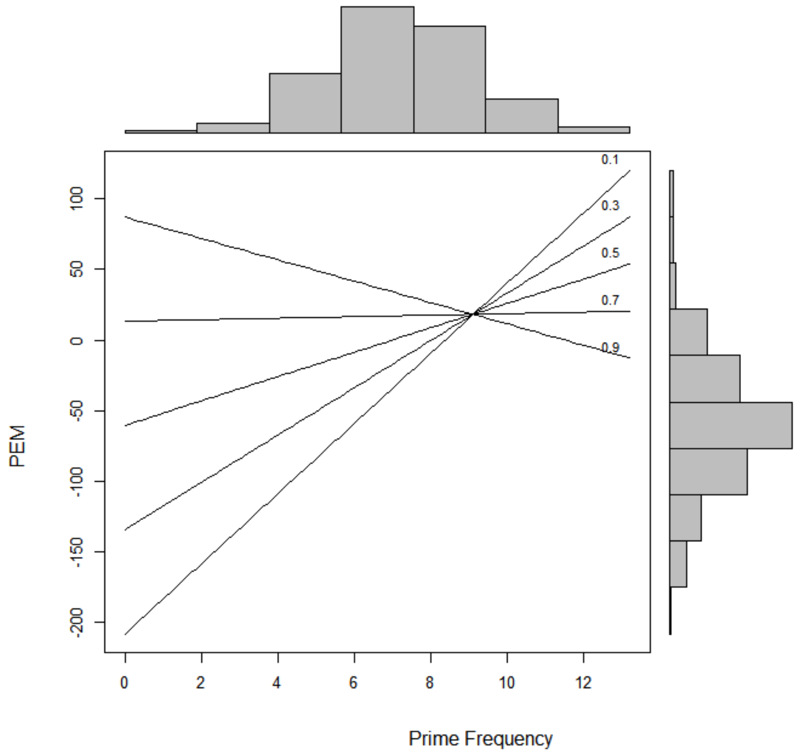


Figure 5



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Prime Frequency