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The effects of semantic transparency and base frequency on the recognition of English complex words

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Short title: Semantic transparency and base frequency

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Abstract

A visual lexical decision task was used to examine the interaction between base frequency (i.e., the cumulative frequencies of morphologically related forms) and semantic transparency for a list of derived words. Linear mixed effects models revealed that high base frequency facilitates the recognition of the complex word (i.e., a "base frequency effect"), but the magnitude of this declines with semantic transparency. These results suggest that the extent to which the constituents of a complex word contribute to its recognition is dictated by semantic transparency. The implications of these findings will be discussed in the context of localist-connectionist models of morphological processing.

Word recognition studies have demonstrated that the recognition of a target word (e.g., *hunt*) is facilitated by the prior consciously available presentation of a complex word that is transparently derived from that stem (e.g., *hunter*), whereas there is no such priming in cases like *corner-CORN* where the relationship between the complex word and its putative stem is semantically opaque (e.g., Feldman & Soltano, 1999; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Rastle, Davis, Marslen-Wilson, & Tyler, 2000). The importance of semantic transparency in the processing of a complex word has been further underlined by Gonnerman, Seidenberg and Andersen (2007) who found an intermediate level of priming for partially transparent prime-target pairs (such as *archer-ARCH*, where an archer is not someone who arches, but the bow that an archer uses does resemble an arch).

Gonnerman et al. (2007) interpret their results within a distributed connectionist framework whereby lexical information (e.g., orthographic form and meaning) is distributed across clusters of units. Morphology is captured by the mapping from a cluster of form units to a corresponding group of semantic ones, mediated by "hidden units" that encode the statistical relationship between form and meaning. By this mechanism, morphology is a graded construct whereby a partially transparent word has a weaker relationship between the form and semantic units compared to a transparent word. The pre-activation of the stem from priming by the whole word therefore declines in proportion to transparency.

A problem for this explanation of morphological representation, however, is its inability to account for findings obtained when the prime is masked from conscious awareness (e.g., Longtin, Segui, & Halle, 2003; Rastle, Davis, & New, 2004). Under these conditions, both transparent and opaque prime-target pairs produce facilitatory priming. Although some studies have found that transparent prime-target pairs produce more priming than opaque ones (e.g., Feldman, Kostic, Gvozdenovic, O'Connor, & Moscoso del Prado Martin, 2012), the fact that opaque items show facilitatory priming at all suggests that, during the early stages of complex word recognition, the mere orthographic appearance of a letter combination as an affix (e.g., the *-er* of *corner*) leads to the decomposition of the complex word into its apparent stem and affix. Such semantically-blind decomposition is a problem for the distributed connectionist approach given that the front-end of the reading system is designed to identify letters and their position in the letter string as opposed to morphological structure (Rueckl, 2010). This raises the question as to how early morphological processing that does decompose opaque words (i.e., morpho-orthographic processing) can be incorporated into a framework that becomes sensitive to the semantic relationship between the prime and target when the former becomes available for conscious processing, as seen in the results from unmasked morphological priming.

To address this concern, one can turn to hierarchically organized localist models such as those proposed by Diependaele, Sandra and Grainger (2009) and Crepaldi, Rastle, Coltheart, and Nickels (2010). A framework that captures the key elements of these models is found in Figure 1. Although the two models have some minor differences in the way morphemes are represented, the two types of morphological processing are captured in essentially the same way. Both models include a morpho-orthographic level, where the letter string activates the form units that correspond to their constituents regardless of any semantic association. For example, the opaque word *corner* activates the orthographic units representing its putative stem and affix (i.e., *corn* and *–er*). These units then proceed to activate the lexical representations through which words are recognized, that is, the "orthographic lexicon" of the Crepaldi et al. model or the "lexical form" level of the Diependaele et al. model. The manner in which these lexical units are activated is also governed by a morphological relationship based on orthography such that the lexical representations for *corner* and *corn* will both be activated by the morpho-orthographic representation of *corn*, even though *corner* is semantically opaque. As a result, the representations that correspond to the opaque stem will be active during the early stages of processing the whole word, which would account for the facilitatory priming between opaque prime-target pairs under masked conditions.

At the higher morpho-semantic level (i.e., the 'Higher Level" of Figure 1) the representations are sensitive to genuine morphological relationships, so activation is only retained in the stem if it has a genuine morphological relationship with the whole word (e.g., the *hunt* in *hunter*). This level provides feedback to the lexical representations so that the activation in the representation of *corn* is eventually reduced (i.e., when *corner* is available for conscious processing, as in the unmasked priming paradigm). There are two ways in which the activation in a unit is reduced. The first is for the activation in *corn* to simply dissipate over time. Alternatively, units can actively compete with one another, such that a complex word will inhibit the representation of its stem depending on the transparency of the word. In both cases, the level of residual activation in the stem is contingent on the degree of semantic overlap with the whole word, and would explain why the magnitude of facilitation under unmasked conditions decreases with transparency in a continuous manner (Gonnerman et al., 2007).

[Figure 1 about here]

Given that these models represent transparent and opaque words in the same way at the form level, with the whole word being activated via the form representation of its stem, it follows that the impact of any factor that is relevant to stem processing should be equivalent for the two types of word. One such factor is base frequency (i.e., the cumulative number of occurrences in the language of all morphologically related forms). For example, the base frequency of *hunter* will include the frequencies of *hunt*, *hunts*, *hunted*, *hunting* as well as *hunter* and *hunters*. Early studies using the lexical decision task (e.g., Burani & Caramazza, 1987; Taft, 1979) provided strong support for a base frequency effect, in which inflected words with a high base frequency were recognized faster than those with a lower base frequency (e.g., *sends* was faster to recognize than *hunts*) even though they were matched on their whole-word frequency (i.e., surface frequency). Because these studies focused on complex words that were transparent, it is uncertain whether a base frequency effect is also applicable to opaque items. In the context of the hierarchical frameworks of Crepaldi et al. (2010) and Diependaele et al. (2009), the stem of the complex word is activated via morpho-orthographic mechanisms every time a morphological relative is presented. Therefore, high base frequency words (HBF) should possess stem representations with a higher baseline of activation relative to low base frequency (LBF) words, and this should hold true at all levels at which the stem is represented. Because surface frequency is matched across the two conditions, a base frequency advantage would imply that the stem contributes activation towards the recognition of the whole word, and HBF words receive more activation than LBF words from their highly activated stems.

It should be noted that constituent properties involve more than just base frequency. For example, studies have found that morphological family size (i.e., the number of transparent complex words that possess the same stem) appears to have a facilitatory effect on word recognition independent of the effects of base frequency (e.g., Bertram, Baayen, & Schreuder, 2000). The base frequency effect emerges for complex words with productive suffixes, while the family size effect does not interact with suffix productivity (Ford, Davis, & Marslen-Wilson, 2010), which has led to the conclusion that family size effects are not a product of morphological processes, but arise from the shared semantic representations of morphologically related words (Ford et al., 2010). Complex words with large families possess a subset of semantic units that are shared by more words than those with a small family size, so words with a large family size will receive more activation feedback from the semantic level which will facilitate their recognition.

On the other hand, base frequency is considered to be captured at the access level where the stems of the complex word are represented (Taft, 1994; 2004), an example of which would be the morpho-orthographic level in the models presented earlier (see Figure 1). Based on those accounts, the morpho-orthographic representation of the stem should contribute activation to the representation of the whole word at the lexical form level or orthographic lexicon (i.e., where recognition occurs), regardless of whether the word is transparent or not. Therefore, an HBF opaque word should receive activation from its stem in the same way that transparent words do and, therefore, should also show a base frequency effect. The aim of the current study, then, is to determine whether the base frequency effect is dictated by semantic transparency. A basic lexical decision task will be used with words that vary on their degree of transparency and on base frequency. If the relationship between the stem and the whole word is not sensitive to transparency (i.e., consistent with the models of Crepaldi et al., 2010, and Diependaele et al., 2009), a base frequency effect should emerge regardless of semantic transparency.

Method

Materials

Semantic transparency was established by means of a rating task in which 35 participants were asked to rate the degree to which the meaning of the first word (i.e., the whole word) was related to the meaning of the second word (i.e., the putative stem). A seven-point Likert scale was used, with a higher value being indicative of a greater degree of relatedness. A total of 272 words ending in a letter cluster that resembled a derivational affix were included in the task, paired with the stems that resulted from removal of that cluster. Targets were then chosen from this pool. Although semantic transparency was treated as a continuous variable, it is important to ensure that the interaction between transparency and base frequency comes from targets that adequately represent the entire spectrum of transparency. To address this concern, the transparency scale was arbitrarily divided into three intervals with 25 items in each. Items with ratings greater than 5 were labeled as Transparent (e.g., *dreamer*), those with ratings equal to 3 and up to 5 were considered to be Partially Transparent (e.g., *archer*), and words with ratings lower than 3 were Opaque (e.g., *coaster*). A list of items used in the study can be found in the Appendix, with their properties reported in Table 1. The base frequency for each word was obtained from the sum of the frequencies of all morphologically related forms (e.g., the base frequency for *dreamer* included the frequencies of *dream*, *dreams*, *dreamt*, *dreaming*, and *dreamer*). If the stem of the opaque word contributes towards the recognition of the whole word, then the frequencies of the words related to that stem need to be included in the base frequency. Therefore, even for opaque words, base frequency was calculated by incorporating the frequencies of the complex forms related to the stem as well as the whole word (e.g., the base frequency for *coaster* included *coast*, *coasts*, *costal*, *coastline*, *coasting*, *coaster*, and *coasters*). Further analyses of the items showed that there was no significant correlation between base and surface frequency within any of the three transparency intervals (r's > .06). Since past studies have suggested that the base frequency effect might interact with surface frequency (Alegre & Gordon, 1999; Baayen, Wurm & Aycock, 2007), surface frequency was controlled for within the statistical analysis. There was also no significant difference across the three rating intervals in terms of log base frequency, *p*'s > .05. Given that the base frequency effect seems to emerge for derived words with productive suffixes, but not unproductive suffixes (Ford et al., 2010), the targets in the current study all possessed the former (according to the classification developed by Ford et al., 2010).

Family size was correlated with base frequency (r = .434, $p < .01$), so the potential confound of family size will be addressed in the statistical analysis. There was no significant correlation between family size and transparency (r = -.025, $p > .05$).

[Table 1 about here]

Nonword foils were also included in the experiment and had the same structure as the real word targets. They consisted of 75 letter-strings composed of nonsense stems attached to existing suffixes (e.g., *chasper*).

Procedure

At the beginning of each trial, a fixation point was presented for 500ms, followed by the target, presented in point 20 Arial font. The target remained on the screen for 1000ms or until a response was given. The order of item presentation was randomized for each participant, and the interval between each trial was 1000ms. Participants were instructed to decide as quickly, but as accurately as possible, whether the letter-string was a real English word or not, using the keyboard to make their response.

Participants

Thirty-one students from the University of New South Wales participated in the study in exchange for course credit. All were English monolinguals.

Results

Correct response times (RT) and error rates (ER) were analyzed using linear-mixed effects (LME) modeling in R (Baayen, Davidson, & Bates, 2008), with the languageR package (Baayen, 2008). Subjects and items were entered as crossed-random factors. A log transformation was applied to the base and surface frequencies. Surface frequency, base frequency and ratings of semantic transparency were entered as fixed effect factors that interacted. The length of the target (in letters), and family size was entered into the fixed effect structure to control for any potential influence of these variables on the main effects and the interaction between transparency and base frequency[1]. Because these fixed factors were continuous variables, they were centered according to their grand means to avoid a spurious correlation between the intercepts and slopes. Subjects and item numbers were entered as random factors[2].

The analysis of RTs included the response times on the previous trial, which was centered as a fixed factor (i.e., CprevRT defined as prevRT – the mean prevRT), while the analysis of ERs did the same in relation to whether an error was found on the previous trial (i.e., prevERR). RTs faster than 200 ms and slower than 2000 ms were excluded and an inverse transformation was applied to the remaining RTs (i.e., -1000/RT) to remove any skew in the data. The analysis of error rates was conducted using the binomial function, with *z* scores being generated. The LME coefficient, *b*, will be reported for the effects of interest to provide insight into the relationship between the fixed effect factor and dependent variable (e.g., a positive coefficient will signify a positive relationship between the two factors), along with the standard error (*SE*).

[Figure 2 about here]

In the RT analyses, base frequency was free to vary non-linearly using the regression modelling strategies package in R (Harrell, 2014). The analysis showed that, when all other fixed effect variables were held constant, the effect of base frequency complied with a linear trend (see Figure 2), as the non-linear relationship between BF and RT was not statistically significant (b = -.08, SE = .06, $|t|$ = 1.45, p > .05). Based on a linear relationship, words with higher BF were recognized faster than those with lower BF (b = -.078, SE = .02, $|t|$ = 3.60, p

< .01). There was a slight trend to suggest that higher transparency ratings led to lower RTs, (*b* = -.038, *SE* = .02, |*t*| = 1.94, *p* = .06), but more importantly, transparency interacted with the magnitude of the base frequency effect, (*b* = -.045, *SE* = .01, |*t*| = 3.42, *p* < .01). That is, the size of the base frequency effect was greater as the words became more transparent.

While controlling for base frequency, there was a significant effect of family size that followed the aforementioned pattern, (*b* = -.012, *SE* = .01, |*t*| = 2.17, *p* < .05), where response times were shorter for words with a large family size. This suggests that family size and base frequency are independent predictors of RTs (Ford et al., 2010). Given that the family size was composed of the number of transparent morphological relatives, family size did not interact with transparency (*b* = -.078, *SE* = .02, |*t*| = .19, *p* > .05). The surface frequency effect was significant (*b* = -.066, *SE* = .02, |*t*| = 3.311, *p* < .01), but unlike previous studies (e.g., Alegre & Gordon, 1999; Baayen, et al., 2007), did not interact with base frequency (*b* = .088, *SE* = .07, |*t*| = 1.26, *p* > .05). This could be attributed to the fact that the items in the current study were mostly restricted to the low surface frequency range (i.e., with only 13 items with surface frequencies over 10 occurrences per million), and the surface frequency effect will only wash-out the influence base frequency when the surface frequency is in the high range. In the analysis of error rates, there was a trend towards a base frequency and transparency interaction, (*b* = -.250, *SE* = .14, |*z*| = 1.85, *p* < .1), but the remaining effects were not significant, *p*'s > .05.

Based on the same LME procedure, further analyses were conducted to determine how the base frequency effect manifested itself across parts of the transparency spectrum (see Figure 3). In the Transparent range, the RT analysis produced a significant base frequency effect (*b* = .187, *SE* = .06, |*t*| = 3.03, *p* < .01) that followed a non-linear trend with a single knot, where the relationship between base frequency and RTs becomes weaker in in the high base frequency range. Partially Transparent items showed a linear trend towards a base frequency effect, ($b = -.064$, $SE = .04$, $|t| = 1.71$, $p < .1$), while no effect was present in the opaque items ($b = .028$, $SE = .03$, $|t| = .11$, $p > .05$). Given that the items within each condition were drawn from a very narrow transparency range, transparency ratings did not have an effect on response times when considering each condition separately, nor did they interact with the base frequency effect (*p's* > .05). In the error rates analysis, there was a significant base frequency effect for the Transparent items ($b = -1.04$, $SE = .42$, $|z| = 2.48$, $p < .05$), while the remaining effects were not significant (*p*'s > .05).

[Figure 3 about here]

Discussion

The results of the current study indicate that the extent to which the recognition of a word benefits from its base frequency is dependent on the word's degree of semantic transparency. Closer examination of specific ranges of transparency revealed that Opaque items do not show a base frequency effect at all, while Transparent and Partially Transparent items show a strong and weak effect respectively. The absence of a base frequency effect for the Opaque items cannot be attributed to a low range of base frequency in those items, given that there was no significant difference across the three transparency conditions in terms of average base frequency. Therefore, it can be argued that base frequency effects apply to words towards the higher end of the transparency spectrum, but not for the words in the low end.

The localist frameworks of morphological processing that have been discussed (i.e., Crepaldi et al., 2010; Diependaele et al., 2009) cannot account for these results, as they propose that the connections between the representation of the stem and their respective whole words are not sensitive to semantic transparency. As a result, stems with a high baseline of activation (i.e., words with a high base frequency) should contribute towards whole-word recognition, and be recognized faster than stems of low base frequency words regardless of transparency.

What is therefore needed is a model that can potentially account for equivalent masked priming effects for transparent and opaque words, but where the former show base frequency effects and the latter do not. One such account is the model proposed by Taft (e.g., Taft, 2006; Taft & Nguyen-Hoan, 2010), to be referred to as AUSTRAL ("Activation Using Structurally Tiered Representations and Lemmas") in order to help differentiate it from the other accounts (see Figure 4). Lemmas are units that capture the correlation between form and meaning, and are therefore, sensitive to morpho-semantic relationships between whole words and their stem.

[Figure 4 about here]

Consistent with the localist accounts summarized in Figure 1, AUSTRAL incorporates automatic decomposition of letter strings via a morpho-orthographic mechanism, where the orthographic representation of the stem and affix are activated. However, unlike the other models, these units then proceed to activate their corresponding lemma units, without the need for an orthographic representation of the whole word. While the Crepaldi et al. (2010) model asserts that recognition in a lexical decision task occurs in the orthographic lexicon, the same role is attributed to the lemmas in the AUSTRAL model. Note that even though the basic definition of *hunter* (i.e., someone who *hunts*) can be ascertained from the constituent morphemes *hunt* and *-er*, derived words must be represented as a whole word at the lemma level so that information specific to that word can be captured (e.g., what a *hunter* wears). In other words, the lemma level of the AUSTRAL model is hierarchically organized such that a derived word is activated via the lemmas of its constituents.

The way in which the lemma units interact with each other is sensitive to semantic relationships. Because there is sufficient semantic overlap, transparent words and their stems will be connected via an excitatory link. Therefore, activation will be retained in the representation of the stem when primed by its derived form, which will lead to facilitation between transparent prime-target pairs regardless of SOA (i.e., masked or unmasked). In contrast, the lemma for an opaque word will be connected to its stem via an inhibitory link to ensure that the opaque stem is not recognized instead of the whole-word (i.e., the lemma for *corner* will inhibit the lemma for *corn*). In this case, the *corner* lemma will be directly activated by the orthographic representations of its constituents (i.e., *CORN* and *ER*), but competes with the lemma for *corn* which is also activated. The activation in the lemma of the opaque stem is eventually suppressed, but with shorter SOA's (i.e., under masked conditions), the system does not have enough time to fully inhibit the lemma of the stem and facilitatory priming can still emerge (see Taft & Nguyen-Hoan, 2010).

Because the connections between lemmas are sensitive to transparency, the AUSTRAL model is also able to account for the interaction between base frequency and transparency. An HBF opaque word might receive more activation from the orthographic representation of its stem compared to an LBF word, but the inhibition from the lemma of its stem will also be proportional to its base frequency and would, therefore, offset that advantage. For example, after morpho-orthographic decomposition of the opaque word *teller*, both the *tell* and *teller* lemmas will be activated through the orthographic unit for *TELL*. While the high frequency of the word *tell* will boost the ease of activation of that orthographic unit, it will also boost the strength of the competing lemma *tell*, hence counteracting any benefit. Thus, the AUSTRAL model would not expect a base frequency effect to emerge from opaque words. Meanwhile, transparent words will be directly recognized via the lemmas of their stems without any counterbalancing inhibition, which means that HBF transparent words will have an advantage over their LBF counterparts.

Consistent with the study by Ford et al. (2010), the current study found a base frequency effect when family size was controlled. To incorporate these effects into the AUSTRAL model, the family size effect could be attributed to the semantic level (Schreuder & Baayen 1997; Ford et al., 2010), where the shared semantic units for words with a large family size are more frequently accessed and provide stronger activation feedback to the lemma level.

If transparency is actually represented in the system as a continuous variable, however, the connection between the lemma of the whole word and its stem cannot be simply dichotomized into excitatory and inhibitory links as described in the version of the AUSTRAL framework depicted in Figure 4 (e.g., Taft, 2006; Taft & Nguyen-Hoan, 2010). One alternative is to consider the connections between lemma units as possessing weightings that range from positive to negative, depending on the degree of semantic overlap. In this way, the weighting on the connection would dictate the extent to which the lemma of the whole word inhibits the lemma of its stem as the whole word is being read, with greater transparency providing less inhibition. This would account for the intermediate priming effects for partially transparent words under unmasked conditions, as the stems of such items would not be inhibited to the same extent as for opaque words. The weighting of the connection would also modulate the amount of activation the lemma of the stem sends to the whole word, whereby more transparent words receive more activation from their stems. Therefore, the amount of activation that a partially transparent word receives from its stem would be less than that for a transparent word, but more than for an opaque one, which would explain why such items exhibit an intermediate base frequency effect.

Of course, it could simply be argued that the intermediate effects for the Partially Transparent condition were a result of the participants treating certain Partially Transparent items as transparent and others as opaque. A dichotomous division of transparency would be maintained by such an account. However, a bimodal distribution would then be expected in the transparency ratings, which is not what was found in the current study. The standard deviation of the semantic ratings for the Partially Transparent condition was very much the same as that for the other two conditions, which is not consistent with a bimodal distribution.

It should be noted that the transparency by base frequency interaction is consistent with a distributed connectionist framework (e.g., Gonnerman et al., 2007). Specifically, stems of high base frequency stems will establish stronger mappings between units of form and meaning. Because transparent words are recognized via the same connections they would show a base frequency effect. Meanwhile, less transparent words may deviate from the pattern of activation that defines its stem, and diminish the effect of base frequency. However, as explained earlier, such a framework lacks utility as it cannot explain masked morphological priming effects.

Based on the present findings, then, it appears that localist models of complex word processing require a mechanism that enables the representation of the stem and whole word to interact in a way that is sensitive to their degree of semantic overlap. A potential mechanism of this kind has been proposed in the AUSTRAL model, in which the connections between the lemmas of the whole word and its stem are sensitive to transparency. The connection could be dynamic so that it allows the stem to contribute to the recognition of the whole word, but also be inhibited by it.

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Appendix

Transparent	**Partially Transparent**	**Opaque**
absently	ageless	badger
adaptable	archer	belly
advertiser	bookish	bully
avoidable	bunker	burger
cleaner	butcher	canal
collectable	classify	coaster
detectable	courtly	colony
dreamer	crafty	crater
dryness	endless	fairy
dullness	flicker	flourish
eater	gutless	flower
effortless	justify	ladder
enjoyable	namely	manner
faintness	overly	miserable
feverish	personify	muster
fiendish	rafter	profession
humidify	rubber	proper
leisurely	sheepish	putty
likeness	signify	shower
nullify	sluggish	stocky
selfish	spineless	surgery
shapely	splinter	tally
stylish	sweater	vanish
tasteless	teller	voucher
thriller	testify	wicker

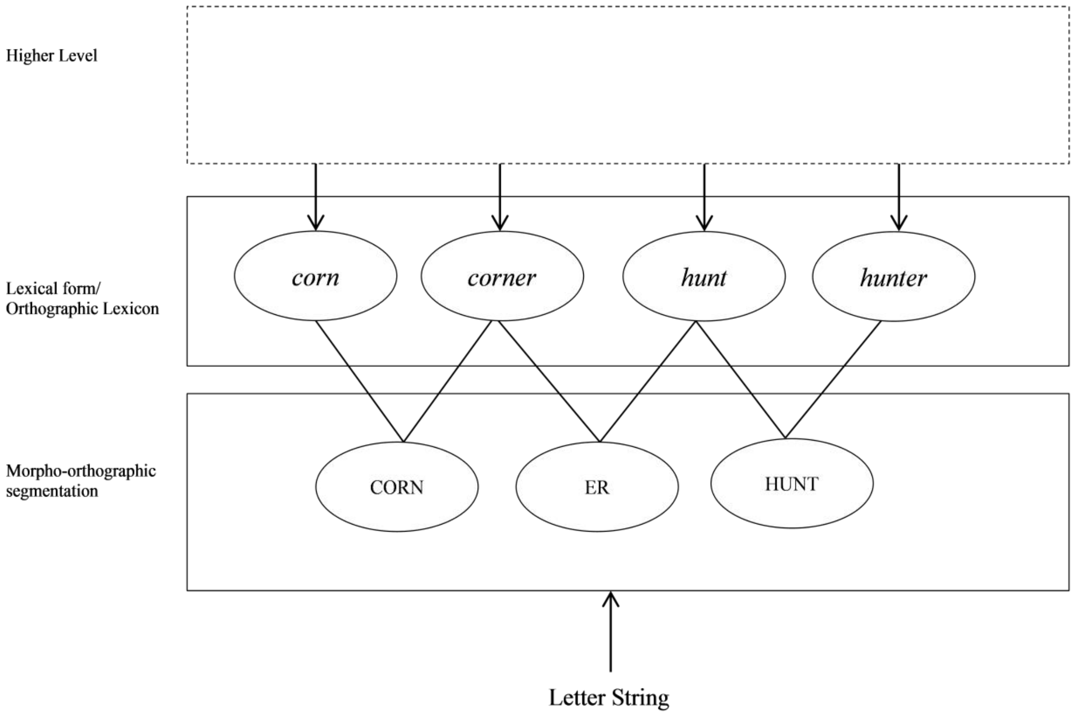

Figure 1. A framework of morphological processing that extracts the basic elements of the model of Diependaele et al. (2009) and Crepaldi et al. (2010). Morpho-semantic processing is represented at the "Higher Level" (i.e., the morpho-semantic level in the Diependaele model, and a combination of the lemma and semantic levels in the Crepaldi model), which provides feedback to the lexical form level and orthographic lexicon.

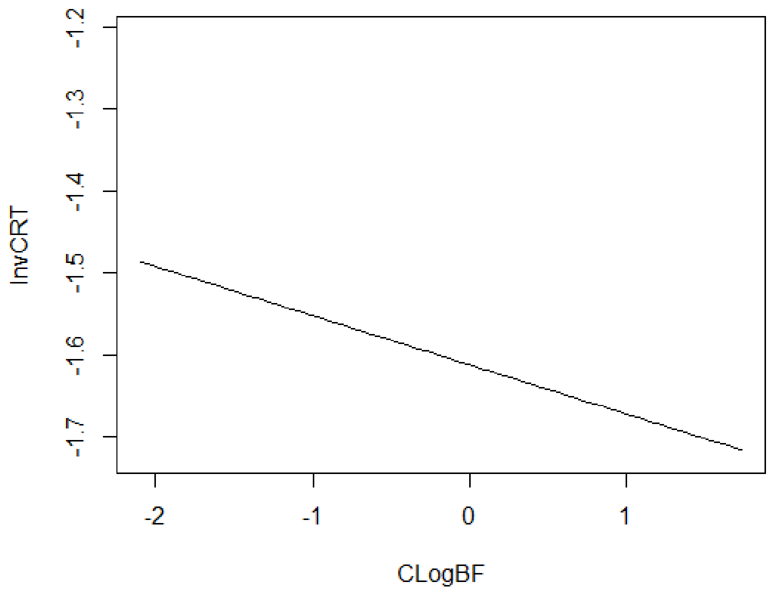

Figure 2. The relationship between base frequency (CLogBF; with log transformation and centred) and RT (InvCRT; with the inverse transformation and centred) for all items.

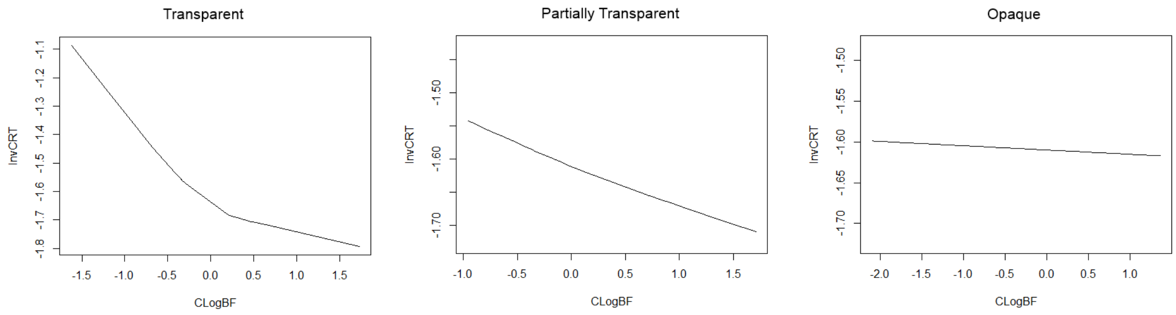

Figure 3. The relationship between base frequency (CLogBF; with log transformation and centred) and RT (InvCRT; with the inverse transformation and centred) for items from different parts of the transparency spectrum (i.e., Transparent, Partially Transparent and Opaque).

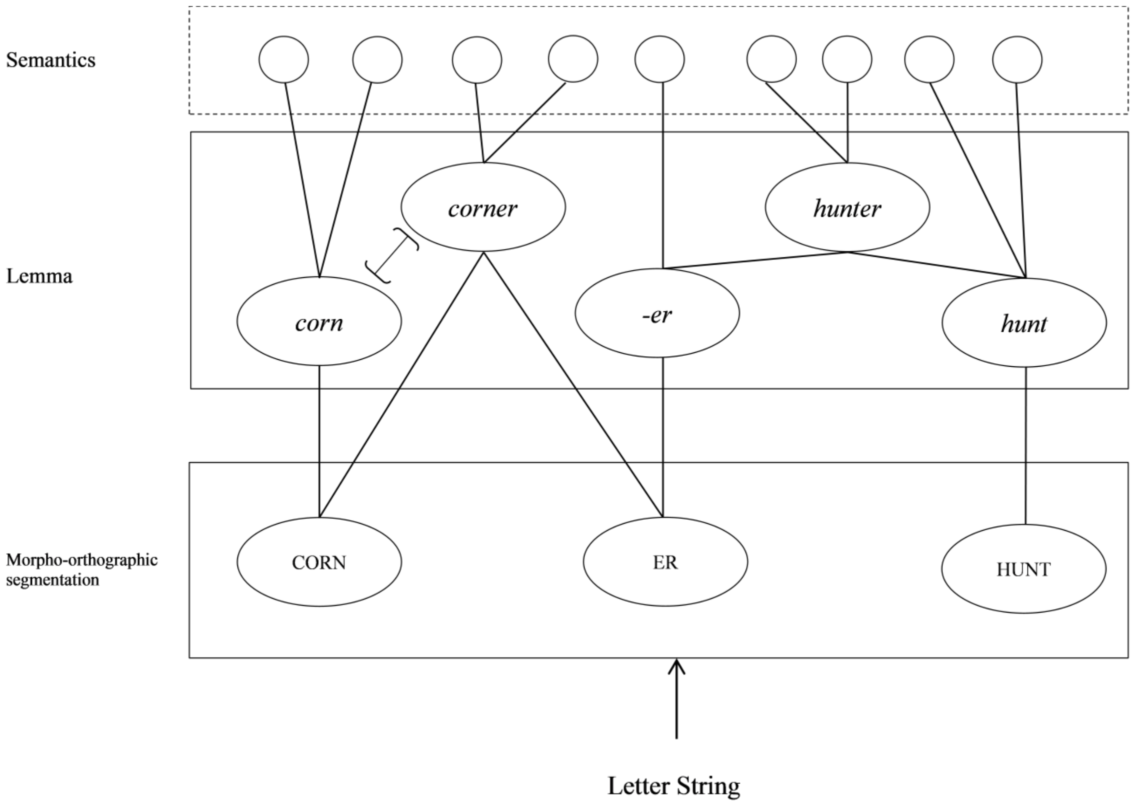

Figure 4. The AUSTRAL model. On the right, the transparent word *hunter* is represented, the lemma of the whole word and its stem are connected by an excitatory link. To the opaque word *corner* is represented, the lemma of the whole-word and stem compete with one another. Instead, lemma of the whole word draws activation from the orthographic representations of its constituents.

Table 1.

Characteristics of experimental stimuli.

Log BF – Log base frequency; Log SF – Log surface frequency; Ratings – the average rating; Length - length of items (in letters); fsize - family size

	Log BF	Log SF	Ratings	Length	fsize
Mean	1.74	0.19	3.94	7.15	11.52
SD	0.83	0.77	1.64	1.41	12.01
Max	3.65	1.61	6.42	11	58
Min	-0.40	-1.41	1.1	5	1

Footnotes

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1 : Affix productivity was also entered as a fixed effect, although a comparison of models shows that the addition of affix productivity did not account for any more variance in the data ($\chi^2 = 1.26$, $p > .05$). A model that did include affix productivity did not change the statistical significance of our reported effects. Productivity values were obtained by dividing the hapax legommena of an affix by its token frequency. These values were taken from Baayen (1994) and Plag, Dalton-Puffer and Baayen (1999).

2: The models described were those that provided the best fit for the data, given by comparing models. Models of a better fit were indicated by significant Chi squared statistics (i.e., $p < .05$).

In all of the LME analyses, by-subject random slopes for surface and base frequency were also considered in the random effects structure although these did not provide a model of better fit.