Title: The deployment of young readers´ visual attention across orthographic strings: the influence of stems and suffixes

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Abstract

The goal of the paper was to investigate whether morphological units - stems and suffixes - influence orthographic processing by modulating visual attention demands to the task. Orthographic processing was measured with a visual one-back task requiring letters to be detected within pseudowords not including stems/suffixes, or containing real stems or real suffixes. Fourth grade children (between 9.5 and 10.5 years old) who read in a transparent orthography of a morphologically rich and agglutinative language (Basque) were tested. The results showed that the presence of morphemes in the strings did not improve letter detection performance though it slightly modulated the distribution of visual attention, showing a bias towards the processing of central letters in the presence of a stem. We suggest that the presence of highly regular and recurrent structures prioritizes stem identification, which when achieved, reduces visual attention deployment across the remaining letters.

Keywords: morphemes, visual attention, orthographic processing, reading development

The deployment of young readers´ visual attention across orthographic strings: the influence of stems and suffixes

How stems and suffixes are processed in written words and pseudowords has been addressed in different languages (Bertram, Schreuder, & Baayen, 2000; Burani, Marcolini, & Stella, 2002; Diependaele, Morris, Serota, Bertrand, & Grainger, 2013; Duñabeitia, Perea, & Carreiras, 2007; Frost, Kugler, Deutsch, & Forster, 2005; Grainger, Colé, & Segui, 1991; Laudanna, Badecker, & Caramazza, 1992; Marslen-Wilson, Bozic, & Randall, 2008; Rastle, Davis, & New, 2004; Taft & Forster, 1976; Taft & Nguyen-Hoan, 2010). Because morphemes are recurrent orthographic regularities, stems and suffixes might be easily internalized as reading experience and skills develop, and activated to boost lexical access. This is supported by studies showing facilitative effects of masked morphological priming in primary school children from the second and third grades in opaque orthographies such as English (Beyersmann, Castles, & Coltheart, 2012), and in semi-transparent orthographies such as French (Quémart, Casalis, & Colé, 2011) and German (Hasenäcker, Beyersmann, & Schroeder, 2016). Additional support comes from studies on transparent orthographies showing the positive influence of morphemes in naming (Italian: Burani et al., 2002), lexical decision (Spanish: Lázaro, Acha, de la Rosa, García, & Sainz, 2017) and writing performance (Spanish: Suárez-Coalla, Martínez-García, & Cuetos, 2017) in the same grades. These studies on developing readers focused on derived words but similar results are reported for inflected words in transparent orthographies (Basque: Acha, Laka, & Perea, 2010; Dutch: Verhoeven & Schreuder, 2011). Thus, it is possible that the early internalization of stems and suffixes could influence letter coding strategies and unfamiliar and familiar word reading from early stages of orthographic processing, particularly in transparent and possibly in semi-transparent orthographies (for a review on morphological processing in skilled reading see: Amenta &

Crepaldi, 2012). In turn, this could affect the deployment of visual attention across letter strings; determining whether or not this is the case is a focus of the present study.

A measure of the ability to deploy visual attention across letter strings is the visual attention (VA) span. It particularly refers to the number of individual elements that can be processed (independently and in parallel) in a multi-element array in a single fixation (Bosse, Tainturier, & Valdois, 2007). The VA span is linked both to orthographic processing (Bosse, Chaves, Largy, & Valdois, 2013) and reading development across alphabetic orthographies varying in transparency (e.g. French: Bosse & Valdois, 2009; Portuguese: Germano, Reilhac, Capellini, & Valdois, 2014; Spanish: Lallier, Valdois, Lassus-Sangosse, Prado, & Kandel, 2014; Dutch: van den Boer, van Bergen, & de Jong, 2015). Despite the existent literature supporting the facilitative role of stems and suffixes in word identification, no work has examined to what extent these internalized structures can influence the reader´s visual attentional strategy for orthographic coding. The aim of this study is to explore this issue in beginning readers of Basque, a transparent and morphologically rich orthography. The study focuses particularly on the visual demands of processing stems and suffixes and the distribution of visual attention across the letter string as a result of such demands.

One way to determine whether the morphological structure of a word affects the deployment of visual attention across letter strings is manipulating the presence of morphemes in orthographic items, following the same rationale of the word identification studies designed to explore this issue with focusing on lexical access. Some studies on developing readers (French and English: Casalis, Quémart, & Duncan, 2015; French: Quémart, Casalis, & Duncan, 2012; Italian: Traficante, Marcolini, Luci, Zoccolotti, & Burani, 2011) orthogonally manipulated the presence of stems and suffixes in pseudowords to explore the role of each type of “regularity” on pseudoword identification. These studies included items with: (a) neither a stem nor a suffix (-stem -suffix), (b) a stem and a pseudo-suffix (+stem -suffix), (c) a pseudo-stem and a suffix (-stem +suffix), and (d) both a stem and a suffix in a non-existing combination (+stem +suffix). A benefit in naming accuracy was shown for pseudowords including either stems or suffixes (Traficante et al., 2011). In lexical decision, studies revealed a disadvantage for pseudowords including both stems and suffixes - in such paradigms, pseudowords are indeed more likely to be mistaken for words (Burani et al., 2002; Casalis et al., 2015; Quémart et al., 2012). For speed, there was a benefit in naming only when stems were present in pseudowords, and a disadvantage in lexical decision either when pseudowords included stems and/or suffixes (Quémart et al., 2012), or when pseudowords included suffixes (Casalis et al., 2015). Overall, this indicates that both stems and suffixes influence processing, possibly with a more salient role for stems in naming and suffixes in lexical decision.

Nevertheless, the aforementioned pattern could also reflect either the difficulty in internalizing suffixes (opaque languages) or the fact that they have not been encountered a sufficient number of times as to be internalized (beginning readers). Indeed, with the exception of one study that was in Italian, a transparent orthography (Traficante et al., 2011), the other two were performed in more opaque orthographies like French (Casalis et al., 2015; Quémart et al., 2012) and English (Casalis et al., 2015). More recent studies also using the lexical decision task have shown that children learning to read in highly transparent languages are able to use internalized regularities very early in reading development (Spanish: Lázaro et al., 2017), and are sensitive both to stems and suffixes as highlighted by facilitation effects on tasks tapping lexical access (German: Hasenäcker et al., 2016).

This supports the view that in transparent languages morphemes are easily internalized due to their frequency but also due to their orthographic stability. This suggests that the effects of morphemes are likely driven by their status as recurrent orthographic units rather than by their link to meaning. Nevertheless, it is also possible that the productivity of morphemes (their combinability with other morphemes in the language) might contribute to their categorization as meaningful units increasing their salience beyond that of other frequent orthographic units. For example, Casalis et al., (2015) studied developing readers of French and English. Their results showed stronger morphological effects (spanning speed and accuracy) for readers of French as compared to readers of English (only accuracy). The authors suggested results could arise not from differences in orthographic transparency but from the morphological richness of the two languages. Specifically, the influence of orthographic transparency (English is more opaque than French) should lead to opposite results: readers of English would rely more on morphemes given the difficulty of decoding words correctly.

The aforementioned results suggest morphological effects could be clearer in reading development in transparent and morphologically rich languages, such as Basque. Basque is an isolated language (for a review on Basque see: Laka, 1996) and is, similarly to Turkish and Finnish, orthographically transparent and agglutinative. In the field of psycholinguistics, Basque has drawn researchers´ attention due to a number of characteristics such as ergativity (Laka & Erdocia, 2005), word order (relatively free at the sentence level although often referred to as an SOV-subject-object-verb: Erdocia, Laka, Mestres-Missé, & Rodriguez-Fornells, 2009), the fact that it is a head-final language (the head of the phrase is placed after its complements, unlike English or French). The agglutinative and compositional nature of Basque make both derivational and inflectional morphemes highly productive and stacked at the end of the stem (articles, case marking, possessives and adverbials are also reflected in suffixes). This leads to the formation of long, morphologically complex words, and morphemes acquire a specific status as highly combinable orthographic units that form words. This can be seen with the word “etxe” – house, which in Basque can be found in "etxea"-the house, "etxearen"-of the house, "etxegile"-housebuilder, "etxera"-to the house, and "etxearentzat"-for the house (Acha, Laka, Landa, & Salaburu, 2014).

Hence, learning to read in Basque might boost the development of specific orthographic knowledge about these regularities and lead readers to use them early in reading development, facilitating the transition towards coarse grained coding strategies (Grainger, Lété, Bertand, Dufau, & Ziegler, 2012). Importantly, sensitivity to morphemes could not only influence orthographic coding but also interact with visual resources available for reading and distributing visual attention across the string.

Eye-movement studies on other agglutinative languages with transparent orthographies support the interaction between word morphological complexity and visuo-orthographic processing in reading. Specifically, one study on skilled Finnish readers´ eye movements when reading long compound words (8-12 letter words) showed that the compounds were processed serially (Hyönä, Bertram, & Pollatsek, 2004), possibly because of visual limitations linked to word length. In the same vein, another study on Finnish showed that the first constituent frequency influenced compound processing for long but not short compounds (Bertram & Hyönä, 2003), also indicating that constituents are processed serially when the whole word cannot be processed in a single fixation. Two other studies also showed that the morphological complexity of words can influence initial landing position in reading (Finnish: Hyönä, Yan, & Vainio, 2018; Uighur: Yan et al., 2014), supporting that morphological complexity at the word level can interact with the visual resources required when reading.

Finally, the influence of visual resources on reading performance and its possible interaction with the presence of morphemes has recently been suggested to occur in Dutch, a transparent but not agglutinative orthography (Law, Veispak, Vanderauwera, & Ghesquière, 2018). Specifically, this masked priming study demonstrated high-functioning adults with dyslexia (high reading comprehension skills) benefited more from the presence of morphological structure than controls, with influences only at the morpho-semantic level (meaning) in the case of controls, but also at the morpho-orthographic level in the adults with dyslexia. Thus, morphological processing may compensate for other difficulties, one of which the authors suggested to be lower visual processing resources.

Objectives and hypotheses of the present study

The above studies suggest that morphemes in orthographic stimuli may impact orthographic coding and the distribution of visual attention resources across orthographic strings. However, previous studies on reading or spelling in *developing* readers of agglutinative languages (Basque: Acha et al., 2010; Finnish: Häikiö, Bertram, & Hyönä, 2011; Lehtonen & Bryant, 2005) have not yet directly addressed the question of whether being exposed to such languages influences visual attentional resources and strategies used in reading.

Here, we aimed to determine how morphological information present in pseudowords affects the deployment of Basque children´s visual attention across letter strings by manipulating the presence of a real stem or a real suffix within the pseudowords. To that end, we used a visual one-back task, a paradigm previously used to measure the deployment of visual attention skills across letter strings and tapping into early perceptual/attentional processes that could influence orthographic coding strategies and interact with lexical access (see below). In this task, a string of letters is briefly presented (for approximately 200 ms, allowing a unique fixation on the string), followed by a target letter. This short presentation duration minimizes phonological/semantic effects. The participant has to report whether or not the target letter was present in the previously presented letter string. This task, when used with a string of consonants within which the target appears, measures the visual attention span (VA span) that is the amount of visual elements that can be processed simultaneously in a multi-element array (Bosse et al., 2007).

Importantly, VA span skills have been linked to pre-orthographic processing reflected by activation of the superior parietal lobule (Lobier, Peyrin, Le Bas, & Valdois, 2012). In addition, performance on a visual one-back paradigm during electrophysiological recording showed that letter detection in both consonant strings and words was related to differences in "attentional" event related potentials (P3b: Lallier, Carreiras, Tainturier, Savill, & Thierry, 2013). Of utmost importance for the present study, studies showed that differences in VA span deployment across consonant strings depended on the availability of multi-letter units in the string. For example Lallier, Acha, and Carreiras (2016), showed that children reading in an opaque orthography (which includes complex and irregular multi-letter graphemes) distributed their VA span resources more homogeneously across letter strings compared to children reading in a transparent orthography (see also: Antzaka et al., 2018). In addition, we know that children with limited access to orthographic lexical knowledge (e.g., dyslexic children) tend to fail at distributing their visual attention homogeneously across the string of letters (Bosse et al., 2013; Lallier et al., 2014; van den Boer et al., 2015). Here, we wanted to determine whether another type of multi-letter orthographic units, i.e. the morphemes, could also modulate visual attention distribution strategies across letter strings.

In the present study, we used the VA span visual one-back task but mainly focus on an adaptation of this task in which the string of letters corresponded either to a pseudoword with a morphologically simple structure (no morpheme) or with a morphologically complex structure (including a real stem with a pseudo-suffix, or a pseudo-stem with a real suffix; +stem-suffix, -stem+suffix[1]). This version of the task, hereafter referred to as the morphological visual one-back task, offers a novel perspective to study visual attentional aspects involved in morphological and orthographic processing: whilst masked priming paradigms (Beyersmann, Grainger, Casalis, & Ziegler, 2015; Hasenäcker et al., 2016; Quémart et al., 2011) tap into the influence of morphemes on automatic lexical access, the morphological visual one-back paradigm (focusing on letter detection rather than word identification) provides a measure of attention deployment across the string allowing us to test performance on specific letter positions in the string. In some aspects, results from the paradigm may be more easily reconciled with those of eye-tracking or optimal viewing position paradigms that are more tuned towards visual processes involved in letter coding needed in word and text reading (e.g., eye-tracking results in adults: Hyönä et al., 2018; Yan et al., 2014).

Thus, the paradigm can elucidate how the presence of familiar orthographic units such as morphemes affects visuo-orthographic processing. Participants´ orthographic knowledge of these morphemes could facilitate processing, in line with results demonstrating easier letter identification in a visual one-back task when the target letter was presented in a word as compared to when it was presented in a consonant string (Lallier et al., 2013). It is possible that any observed effects of morphemes on performance are related to the frequency of their orthographic forms (statistical regularities) rather than to their status as meaningful units. Whether this is indeed the case is an issue we will return to in the discussion.

In the morphological visual one-back paradigm, due to the transparency of Basque, we expected a left-to-right decrease in target letter detection performance. Secondly, we expected easier processing of morphemic orthographic units to increase the availability of visual attentional resources to process the remainder of the pseudoword (the non-real constituent), thus boosting target letter detection across the whole letter string for morphologically complex as opposed to morphologically simple stimuli. Thirdly, we predicted target letter detection will be facilitated when appearing within real stems or real suffixes (identified as recurrent regularities) as they would be part of orthographic multi-letter units consolidated in memory and, thus, accessed automatically. We considered this would lead to differences in letter detection performance depending on the type of real morpheme (stem or suffix) included in the pseudoword since the known orthographic multi-letter units would appear in different positions of the string. Lastly, we expected to find significant correlations between performance on the classic VA span visual one-back task (consonant strings) and our morphological visual one-back task (pseudowords), especially in the absence of morphemes, since the presence of morphemes could facilitate processing of multi-letter orthographic units (for evidence on morphemes modulating visuo-orthographic processing load also see: Antzaka, Acha, Carreiras, & Lallier, 2019) and reduce the visual processing load (as is the case for words: Lallier et al., 2013).

Methods

Participants

Participants were children attending the fourth grade of primary school education in the Spanish-Basque region of the Basque Country (Spain) and were native speakers of Basque, with Spanish as a second language. In the school, teaching was mostly in Basque, with only courses on English and Spanish language taught in the respective languages. This age was chosen to assure that children had enough reading experience as to be prone to facilitative effects of the presence of morphemes (Lázaro et al., 2017). Language background information was acquired through a questionnaire completed by the child´s (parent or) legal guardian. Thirty-two fourth grade children were tested, and two children were removed from the analysis, leaving a total of 30 children. One of the two children was removed because their first language was Spanish. The second child was removed because of low performance on the WISC non-verbal intelligence test (see below). The parent/guardian of each child was informed about the techniques, duration and goals of the study and provided written consent for the child´s participation. The project was approved by the ethical committee of the Basque Center on Cognition, Brain and Language and was performed in accordance to relevant guidelines and to the declaration of Helsinki.

Morphological visual one-back task

Stimuli consisted of 216 seven-letter pseudowords without letter repetition in a single string (see Appendix A for a full list of the items in Tables A1 and A2). Of the 216 pseudowords, 144 were used in trials in which the target letter was present in the pseudoword (target-present trials), and 72 were used in trials in which the target was absent from the pseudoword (target-absent trials). Half the trials included morphologically simple pseudowords (-stem-suffix) and the rest included morphologically complex pseudowords.

Morphologically complex pseudowords were constructed including a stem or a suffix (+stem-suffix/-stem+suffix). Target letters were limited to three vowels (*"a"*, *"i"*, *"o"*) and their presentation was restricted to one of three target positions, initial (first), central-fixation (fourth), and final (seventh). These restrictions were implemented to closely control the number of times the target letters appeared in each of the possible target positions across all trials (not only those in which they were presented as targets). Moreover, due to debate as to whether vowels are processed differently than consonants (e.g., Carreiras, Gillon-Dowens, Vergara, & Perea, 2009; Duñabeitia & Carreiras, 2011; Perea, Marcet, & Acha, 2017) morphologically simple and complex items in target-present and absent trials were matched on the mean number of overall (*ps* > .54) and target (*ps* > .27) vowels per pseudoword[2]. Pseudowords across conditions were also matched on mean log bigram token frequency (morphologically complex pseudowords: Mean_{btf} =1.56, morphologically simple pseudowords: Mean_{btf} =1.57) as calculated based on the E-Hitz database (Perea et al., 2006). Frequencies of stems and suffixes were also matched across conditions ($\text{Mean}_{\text{stemFreq}}$=118; $\text{Mean}_{\text{suffixFreq}}$=139 per million) according to the EHME database (Acha et al., 2014). Six stems (*“aho”*, *“ate”*, *“igo”*, *“oin”*, *“ile”*, *“ohe”*) and suffixes (*“koi”*, *“txo”*, *“era”*, *“tza”*, *“aro”*, *“gai”*) were each used nine times to construct the morphologically complex pseudowords of both the target-present and target-absent trials[3]. Further information on the morphemes is presented in Table A3 of the Appendix.

Target letters appearing in the fourth position of a morphologically complex pseudoword were always adjacent to a morpheme, while target letters in the first and seventh position were within the morpheme or the pseudomorpheme. Target letters were presented as targets an equal number of times in each position within the target-present and absent trials. The number of times each letter appeared in each letter position in each condition was also calculated in order to avoid clear repetition of specific patterns in certain conditions (e.g., infrequent letters appearing consistently in morphologically complex but not simple pseudowords).

Overall, the construction of the stimuli was aimed to perform two critical comparisons (see objectives and hypotheses). First, to test whether the presence of a real morpheme would provide an overall advantage in target detection performance, we sought to compare letter detection across the three target positions between morphologically simple and morphologically complex pseudowords. Second, to test whether the type of familiar morpheme would have a different effect on performance, we aimed to compare letter detection across the three target positions between complex pseudowords with a real stem (+stem-suffix) and those including a real suffix (-stem+suffix).

Procedure: Stimuli were presented on a white screen in black upper-case Arial font and children were seated 100 cm away from the screen. Stimulus width varied between 5.2° and 5.5° of visual angle and the centre-to-centre distance between each adjacent letter was 1.2°, to minimize lateral masking effects. In each trial, a central fixation point was displayed for 1000 ms, followed by the centred letter string for 200 ms. The letter string was followed by a white screen lasting 100 ms and a single letter (target) appearing centrally (in relation to the horizontal axis) and below the median horizontal line. Target letters were presented in red with a bold-italic font to reduce visual similarity with the preceding letter strings. Children were instructed to respond as fast as possible by pressing the “Alt Gr” key (on the right) when the target letter was present in the previously presented consonant string, and the “Alt” key (on the left) when it was absent. The target disappeared after the child’s response, and a screen with a question mark in the centre was presented until the experimenter pressed the left mouse button to initiate the next trial. Responses were recorded between 150 and 3000 ms after the target appeared. Trial order was randomized. The experimenter pressed the button to proceed to the next trial (Figure 1). At the beginning of the task, six practice trials were provided with feedback. Accuracy was recorded for each trial based on which an individual sensitivity (average d-prime or *d’* sensitivity index) was calculated separately for each of the analysed conditions.

<Insert Figure 1 here>

Visual Attention Span: Visual one-back task

VA span skills were assessed with a visual one-back paradigm (Lallier et al., 2016). Thirteen consonants present in the Basque and Spanish alphabet (B, D, F, G, H, K, L, M, N, P, R, S, T) were used to create the consonant strings that did not include multi-letter graphemes or word skeletons of Basque or Spanish. Letters were not repeated in a single letter string. Stimuli included 104 five-consonant strings, 65 of which were used on target-present trials (the 13 consonants were presented five times as target, once at each position in the string) and the rest on target-absent trials (the 13 consonants were presented three times as targets). Children were seated 70 cm away from the screen. Otherwise the paradigm was the same as presented in the morphological visual one-back task. At the beginning of the task five practice trials were provided with feedback. Accuracy was recorded for each trial based on which an individual VA span score (average *d'* sensitivity index) was calculated.

Control Tasks

Non-verbal intelligence. Non-verbal reasoning skills were assessed using the matrix reasoning subtest of the WISC battery (Fourth Edition: Wechsler, 2003) that provides a measure of fluid reasoning. The reliability of the test is .89 (calculated based on the split half method). The individual scores were converted to scaled scores based on chronological age.

Single letter processing. An individual index of single letter processing was calculated with a task including all consonants used in the VA span task. A single consonant was presented in the centre of the screen in each trial for one of five possible presentation durations (33, 50, 67, 84 and 101 ms). The consonant was followed by a 50 ms mask and children were asked to name the preceding consonant. A weighted sum of performance on the task (score at 33 ms * 5 + score at 50 ms * 4 + score at 67 ms * 3 + score at 84 ms * 2 + score at 101 ms, Bosse et al., 2007; Bosse & Valdois, 2009) was used.

General Procedure

The presented tasks were administered as part of a larger battery performed with the teachers´ permission during school hours and in a quiet room within the school. Computer-based tasks were administered using Presentation ®.

Data Analyses

A first Type II ANOVA aimed to test the effect of Target Position but also whether there would be an overall benefit in letter detection performance due to the presence of a real morpheme (either a stem or a suffix) in the complex pseudowords. This ANOVA included performance across all items, and *d'* sensitivity on the morphological visual one-back task was analysed with Target Position (first, fourth, or seventh) and Morphological Complexity (simple vs. complex pseudowords) as within-subject factors. Then, a second Type II ANOVA including only the performance on morphologically complex pseudowords was conducted on *d'* values, with Target Position (first, fourth, or seventh) and Morphological Structure (+stem-suffix, -stem+suffix) as within subject factors. This second ANOVA aimed to further test whether the presence of a familiar stem would have a different effect on letter detection performance than the presence of a familiar suffix. Greenhouse-Geisser corrections were used when assumptions of sphericity were violated. Post-hoc comparisons were performed using least-square means (lsmeans package: Lenth, 2016) that compute degrees of freedom based on the Satterthwaite approximation. Significance of multiple comparisons was adjusted using Hochberg corrections. ANOVAs and post hoc tests were performed using the ULL R Toolbox (Hernández-Cabrera, 2012).

Finally, a linear mixed regression model was used to define the degree to which average VA span sensitivity on the VA span visual one-back task was related to performance on the morphological visual one-back task. *P* values were calculated using the Satterthwaite approximation (lmerTest: Kuznetsova, Bruun Brockhoff, & Haubo Bojesen Christensen, 2014). Average *d'* sensitivity across all target positions for each of the three types of pseudoword (-stem-suffix, +stem-suffix, -stem+suffix) was used as the outcome variable[4]. Average *d'* sensitivity on the VA span visual one-back task was used as a continuous predictor of interest and was allowed to interact with the categorical factor type of pseudoword. Age, age-standardised non-verbal intelligence and single letter processing skills were included as control variables. VA span skills and the control variables were mean-centred and by-subject intercepts were included in the random effects (random by subject slopes for type of pseudoword could not be included since there were not enough observations for them to be computed and this led to convergence issues). Values for marginal and conditional R-squared were also reported (Barton, 2018).

Results

Descriptive statistics on children´s age, standardised non-verbal intelligence, single letter processing and VA span skills are presented in Table 1.

<Insert Table 1 here>

Morphological visual one-back task

Sensitivity scores *(d')* on each target position and for each type of pseudoword[5] are presented in Table 2 and accuracy scores for these conditions are also presented in appendix Table A4. The original *d'* scores were analysed since they were normally distributed.

The Type II ANOVA on *d'* values across all stimuli (i.e., both morphologically complex and simple pseudowords) showed an effect of Target Position ($F(2,58) = 8.66$, $p = .001$, $\eta_p^2 = .39$), but no other main effects or interactions ($ps > .93$). The post-hoc comparisons on the effect of Target Position (*p* values adjusted for three tests based on Hochberg corrections) indicated that sensitivity declined from left to right: sensitivity was higher for targets appearing in the first as compared to the fourth ($t = 2.69$, $df = 145$, $p = .01$) and seventh positions ($t = 5.23$, $df = 145$, $p < .001$), and higher on the fourth than on the seventh position ($t = 2.54$, $df = 145$, $p = .01$, Figure 2).

<Insert Table 2 here>

<Insert Figure 2 here>

To further examine the potential role of suffixes and stems on letter detection strategies, a second Type II ANOVA on the *d'* value across the morphologically complex pseudowords (+stem-suffix and -stem+suffix) was conducted. The analysis of this specific item set also revealed an effect of Target Position ($F(2,58) = 7.25$, $p = .002$, $\eta_p^2 = .33$), and a trend for a Target Position by Morphological Structure interaction ($F(2,58) = 3.14$, $p = .05$, $\eta_p^2 = .15$). The post-hoc comparisons on the Target Position by Morphological Structure interaction (*p* values adjusted for nine tests based on Hochberg corrections) showed no differences on sensitivity to target letters in each position between the two types of pseudoword ($ps > .33$).

However, within each type of morphological structure, the pattern of sensitivity across target positions differed. For pseudowords including a real stem (+stem-suffix), sensitivity was higher for targets appearing in the first as compared to the fourth (*t* = 2.66, *df* = 145, *p* = .03) and the seventh positions (*t* = 3.24, *df* = 145, *p* = .009), while performance was similar on the fourth and seventh position (*t* = 0.59, *df* = 145, *p* = .83). For pseudowords including a pseudo-stem (-stem+suffix), sensitivity was similar for targets appearing in the first and fourth positions (*t* = 0.22, *df* = 145, *p* = .82), and in both cases higher than on the seventh position (first - seventh: *t* = 2.96, *df* = 145, *p* = .018; fourth - seventh: *t* = 2.74, *df* = 145, *p* = .03, Figure 3).

<Insert Figure 3 here>

Relation between performance on the morphological and VA span visual one-back tasks

We aimed to explore to what extent general letter detection abilities in the VA span visual one-back task could be related to letter detection in our experimental morphological visual one-back task. Amongst our control variables, only single letter identification was linked to performance on the morphological visual one-back task regardless of the type of pseudoword (*ps* < .05), as age and age-standardised non-verbal intelligence were not linked to performance. As expected, VA span skills were also linked to performance on the morphological visual one-back task. More specifically, when performance on morphologically complex pseudowords with a pseudo-stem (-stem+suffix) was set as the reference level, there was a significant effect of VA span skills (Intercept = 1.62, β = 0.62, *SE* = 0.28, *p* = .03, see Table 3). The interactions between VA span and the type of pseudoword (-stem-suffix/+stem-suffix) showed that the link between VA span and performance on the morphological visual one-back task was significantly different only in the case of morphologically complex pseudowords with a real stem (+stem-suffix). This indicated that, while the effect of VA span was also present when performance on morphologically simple pseudowords (-stem-suffix) was set as the reference level (Intercept = 1.54, β = 0.53, *SE* = 0.28 , *p* = .06, see Table A5 a in appendix), such an effect was not present when performance on morphologically complex pseudowords with a real stem (+stem-suffix) was set as the reference level (Intercept = 1.60, β = 0.07, *SE* = 0.28, *p* = .81, see Table A5 b in appendix). Thus, better performance on the standard VA span task led to better performance on the morphological visual one-back task in the absence of morphemes and when a pseudo-stem and a real suffix (but not a real stem) was present (Figure 4). The conditional R-squared was 0.78 and the marginal R-squared was 0.31.

<Insert Table 3 here>

<Insert Figure 4 here>

Discussion

The present study tested how the morphological structure of a non-familiar letter string affects visuo-orthographic processing. Particularly, we wanted to determine how the presence of stems and suffixes influences the deployment of visual attention across the string. Many studies have explored the influence of stem/suffix regularities on word identification by manipulating the presence of such regularities in pseudowords (Burani et al., 2002; Casalis et al., 2015; Quémart et al., 2012; Traficante et al., 2011), showing that children are able to visually capture the presence of morphemes during orthographic coding, possibly boosting word recognition. Recent studies also argue in favour of a key role of stems as significant units for lexical access particularly at early ages (Beyersmann, Grainger, et al., 2015; Hasenäcker, Schröter, & Schroeder, 2017). However, the word identification tasks used in these studies are designed to explore lexical access, and not early letter coding and visual attention processes that do not require lexical activation. To date, no study has explored whether children are sensitive to stems and suffixes at early stages of visuo-orthographic processing, and whether this modulates their visual attention strategies to code letters. Our aim was to explore this issue in fourth grade Basque children, examining the influence of these recurrent regularities in their deployment of visual attention across strings. Since Basque is a very transparent orthography subject to many suffix and composition rules, fourth grade children should have been sufficiently exposed to the orthography as to have internalized morphemes (Acha et al., 2010).

A key hypothesis was that if children had internalized these regularities as significant orthographic units, this might boost the transition towards processing increasingly large units within a single fixation. This would in turn modulate the deployment of their visual attention across the string of letters, something that could have an impact on their transition from alphabetic to orthographic reading (Ehri, 2005).

Overall, we observed the expected leftward bias in the distribution mode of the visual attention resources used to identify letters in pseudowords (Lallier et al., 2013). In contrast to our predictions, performance on the morphological visual one-back task was similar between morphologically complex and simple pseudowords, and between morphologically complex pseudowords with a real stem and a pseudo-stem. This suggests that the presence of a morpheme did not lead to *better* letter identification performance and better allocation of VA span resources across the string.

One reason for the apparent absence of the “morphological benefit” reported in previous studies (lexical decision paradigm: Casalis et al., 2015; Quémart et al., 2012; naming paradigm: Traficante et al., 2011; and for a “morphological disadvantage” in letter search: Beyersmann, Ziegler, & Grainger, 2015) could be the paradigm used. Our task was designed to tap into early letter coding processes and did not require lexical access. Thus, the rapid presentation of the letter string could have reduced the influence of morphemes on processing, minimising the boost classically observed through morphological semantic access. Moreover, the fact that we did not include a real word condition (+stem+suffix) might have boosted sublexical effects over lexical ones.

Yet, and in support of our hypothesis, when only the items containing orthographic regularities (i.e., morphemes) were examined, we observed that the morphological structure of the complex pseudowords modulated the pattern of letter identification across the string, indicating a distinct influence of stems or suffixes on the deployment of visual attention. For pseudowords including a pseudo-stem and a real suffix (-stem+suffix), attention was directed towards the pseudo-stem since the target letters within the pseudo-stem (initial and central positions) were identified similarly accurately. On the contrary, for pseudowords including a real stem and a pseudo-suffix (+stem-suffix), we observed a more homogeneous spread of attention away from the stem (i.e., across the pseudo-suffix) with similar performance on central and final positions of the pseudoword.

One explanation for this result is that stems and suffixes might be processed quite differently. On the one hand, real suffixes could be identified early and efficiently as orthographic units (Quémart et al., 2012) through mechanisms such as affix stripping (Taft & Forster, 1975) or chunking (Grainger & Ziegler, 2011), thus freeing cognitive resources for the orthographic processing of the stem (here the pseudo-stem). This would lead to more available visual attentional resources that could be spread homogeneously across the initial and central letters of the pseudoword, hence limiting the left-to-right performance decrease related to reading direction constraints. On the other hand, the presence of real stems in the string could lead to different effects due to their prominent informative role at the lexical level (e.g., Diependaele, Ziegler, & Grainger, 2010; Grainger & Beyersmann, 2017; Taft & Forster, 1975). More specifically, real stem identification could in fact occupy cognitive resources at higher levels of processing, for instance starting activation of potential lexical candidates, thus reducing the visual attentional demands for processing the “remaining” right side of the pseudoword. This hypothesis fits well with our findings about the link between VA span skills (measured for consonant strings and thus reflecting a “purer” measure of VA span) and letter identification performance on our morphological visual one-back task: a significant relation was found between VA span skills and pseudowords without morphemes or pseudowords with a pseudo-stem. This was not the case for pseudowords with a real stem, suggesting that the pattern diverged from that found in the items where no cue at the left of the string boosted prelexical access. Taking into account that in transparent orthographies children tend to decode when words are unknown, it might be reasonable to think that only familiar structures at the left (the stem) might change the natural left to right bias in letter coding processes slightly altering the visual span pattern. This fits with the edge aligned word activation proposal (Grainger & Beyersmann, 2017) assuming that when facing a word the reader activates all edge aligned (stems, morphemes, words) structures that could fit the stimulus with a bias towards the left where the stem appears. The tendency to give priority to the first letter systematically supports this view. However, this theory is mostly based on evidence from word identification studies and it is possible that due to short presentation durations these processes cannot be observed.

The presented explanation assumes that the observed effects are driven by the status of morphemes as meaningful units. Nevertheless, as aforementioned, observed results could also be driven by the frequency of the orthographic units constituting the morphemes (statistical regularities). Given the composition of our stimuli we were not able to directly test this alternative. Yet we performed exploratory analyses (see Supplementary Material) testing whether the observed effects would persist even after controlling for the frequency of the orthographic units (initial and final trigram frequencies of the pseudowords). The results provide support for the frequency of the orthographic units playing a role in the observed effects. Specifically, while overall effects of morphological structure were still observed after controlling for the frequency of the orthographic units, performance was also clearly influenced by frequency of orthographic units (particularly frequency of the orthographic units appearing in the position of the suffix). This could suggest that there might be additive effects at play: while the frequency with which morphemes appear in written language improves their internalization and development of orthographic knowledge, their status as meaningful units further boosts this process (in line with the lexical quality hypothesis: Perfetti & Hart, 2002). It should be noted that future studies are needed in order to provide a direct test of this hypothesis by orthogonally manipulating morpheme presence and orthographic unit frequency across conditions.

Overall, our data suggest that the influence of morphemes on the distribution of visual attention is small since an improvement in letter detection performance was not observed. Yet, the modulation in the pattern of letter detection in pseudowords with a real stem as opposed to a real suffix suggests that stems and suffixes might play a different role in orthographic coding, in particular regarding visual attention distribution strategies across letter strings. Since visual attention distribution strategies might be particularly relevant for developing word-specific knowledge from basic letter-sound mappings (Castles & Nation, 2006), we could consider that the morphologically rich nature of certain orthographies might boost the transition from partial to full alphabetic reading through the adaptation of visual attention deployment.

Notably, these data were collected in a sample of Basque children, learning to read a highly transparent and morphologically rich orthography. Questions thus arise regarding whether any influence of stems and suffixes on the deployment of visual attention would be seen in languages with different characteristics. Previous research suggests that developing sensitivity to morphemes in reading depends on factors such as transparency and morphological richness of the language (Casalis et al., 2015; Diamanti, Goulandris, Campbell, & Protopapas, 2018). The highly compositional nature of Basque (e.g., from 22.7 million words in the EHME Basque database, only 53.310 are lemmas) implies that morphemes are extremely productive and that the presence of pre-orthographic facilitative effects might be stronger in Basque than other languages that are less compositional but similarly transparent (e.g., Spanish). Moreover, it could be the case that in languages with a more opaque orthography, the influence of morphemes would be enhanced due to their additional value in disambiguating pronunciation (Bowers & Bowers, 2017; Peereman, Sprenger-Charolles, & Messaoud-Galusi, 2013; Rastle, 2018; although see: Casalis et al., 2015). Such cross-linguistic differences would further support that the internalisation of word structure could be based on different types of orthographic units depending on the orthographic and phonological properties of each language (Grainger & Ziegler, 2011; Perry, Ziegler, & Zorzi, 2007). Further work studying the influence of morphemes on visual demands in reading is needed to specify the impact of orthographic transparency, morphological richness, and reading experience/skill. This could shed light on how visual attentional and orthographic processing strategies are shaped by orthography-specific demands during reading development.

Lastly, it is important to highlight some of the potential limitations of this study. First, a larger sample size could have provided a more robust test of our hypotheses. Second, a cross-sectional design would have allowed us to study how performance on the morphological visual one-back task differs depending on reading skill. Third, knowledge on the characteristics of the morphemes we used was based on databases of Basque (Acha et al., 2014; Perea et al., 2006) that do not reflect written exposure to these items during childhood and schooling. To our knowledge, such Basque databases do not exist. This makes it difficult to quantify the exposure of our participants to the stems and suffixes included in our stimuli. Future Basque studies might need to separately measure children´s orthographic knowledge of the specific morphemes used to help address this issue.

Conclusions

The key finding of the present study is that while the presence of stems and suffixes did not provide an overall boost in letter detection in our visual one-back paradigm, the specific knowledge about stems and suffixes during childhood might slightly modulate letter coding strategies through the deployment of visual attention across letter strings (also see: Burani, Marcolini, Traficante, & Zoccolotti, 2018; Law et al., 2018). This modulation might be partly attributed to the frequency with which these orthographic units are encountered in written language. Whether visual attention distribution strategies modulate the time-course of reading development and the progression towards the orthographic lexical stage is a question for future research.

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References

Acha, J., Laka, I., Landa, J., & Salaburu, P. (2014). EHME : a new word database for research in basque language. *The Spanish Journal of Psychology, 17*, E79.

Acha, J., Laka, I., & Perea, M. (2010). Reading development in agglutinative languages: evidence from beginning, intermediate, and adult Basque readers. *Journal of Experimental Child Psychology, 105*, 359–375. https://doi.org/10.1016/j.jecp.2009.10.008

Amenta, S., & Crepaldi, D. (2012). Morphological processing as we know it: an analytical review of morphological effects in visual word identification. *Frontiers in Psychology, 3*, 232. https://doi.org/10.3389/fpsyg.2012.00232

Antzaka, A., Acha, J., Carreiras, M., & Lallier, M. (2019). Does the visual attention span play a role in the morphological processing of orthographic stimuli? *Quarterly Journal of Experimental Psychology*, *72*, 1704–1716. https://doi.org/10.1177/1747021818806470

Antzaka, A., Martin, C., Caffarra, S., Schlöffel, S., Carreiras, M., & Lallier, M. (2018). The effect of orthographic depth on letter string processing: the case of visual attention span and rapid automatized naming. *Reading and Writing: An Interdisciplinary Journal*, *31*, 583–605. https://doi.org/10.1007/s11145-017-9799-0

Barton, K. (2018). *MuMIn: Multi-Model Inference*. Retrieved from https://cran.r-project.org/package=MuMIn

Bertram, R., & Hyönä, J. (2003). The length of a complex word modifies the role of morphological structure: Evidence from eye movements when short and long finnish compounds. *Journal of Memory and Language*, *48*, 615–634. https://doi.org/10.1016/S0749-596X(02)00539-9

Bertram, R., Schreuder, R., & Baayen, R. H. (2000). The balance of storage and computation in morphological processing: the role of word formation type, affixal homonymy, and productivity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 489–511. https://doi.org/10.1037//0278-7393.26.2.489

Beyersmann, E., Castles, A., & Coltheart, M. (2012). Morphological processing during visual word recognition in developing readers: Evidence from masked priming. *The Quarterly Journal of Experimental Psychology*, *65*, 1306–1326. https://doi.org/10.1080/17470218.2012.656661

Beyersmann, E., Grainger, J., Casalis, S., & Ziegler, J. C. (2015). Effects of reading proficiency on embedded stem priming in primary school children. *Journal of Experimental Child Psychology*, *139*, 115–126. https://doi.org/10.1016/j.jecp.2015.06.001

Beyersmann, E., Ziegler, J. C., & Grainger, J. (2015). Differences in the processing of prefixes and suffixes revealed by a letter-search task. *Scientific Studies of Reading*, *19*, 360–373. https://doi.org/10.1080/10888438.2015.1057824

Bosse, M. L., Chaves, N., Largy, P., & Valdois, S. (2013). Orthographic learning during reading: the role of whole-word visual processing. *Journal of Research in Reading*, *38*, 141–158. https://doi.org/10.1111/j.1467-9817.2012.01551.x

Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: the visual attention span deficit hypothesis. *Cognition: International Journal of Cognitive Science*, *104*, 198–230. https://doi.org/10.1016/j.cognition.2006.05.009

Bosse, M. L., & Valdois, S. (2009). Influence of the visual attention span on child reading performance: a cross-sectional study. *Journal of Research in Reading*, *32*, 230–253. https://doi.org/10.1111/j.1467-9817.2008.01387.x

Bowers, J. S., & Bowers, P. N. (2017). Beyond phonics: the case for teaching children the logic of the English spelling system. *Educational Psychologist*, *52*, 124–141. https://doi.org/10.1080/00461520.2017.1288571

Burani, C., Marcolini, S., & Stella, G. (2002). How early does morpholexical reading develop in readers of a shallow orthography? *Brain and Language: A Journal of Clinical, Experimental, and Theoretical Research*, *81*, 568–586. https://doi.org/10.1006/brln.2001.2548

Burani, C., Marcolini, S., Traficante, D., & Zoccolotti, P. (2018). Reading derived words by Italian children with and without dyslexia: The effect of root length. *Frontiers in Psychology*, *9*, 647. https://doi.org/10.3389/fpsyg.2018.00647

Carreiras, M., Gillon-Dowens, M., Vergara, M., & Perea, M. (2009). Are vowels and consonants processed differently? Event-related potential evidence with a delayed letter paradigm. *Journal of Cognitive Neuroscience*, *21*, 275–288. https://doi.org/10.1162/jocn.2008.21023

Casalis, S., Quémart, P., & Duncan, L. G. (2015). How language affects children’s use of derivational morphology in visual word and pseudoword processing: evidence from a cross-language study. *Frontiers in Psychology*, *6*, 452. https://doi.org/10.3389/fpsyg.2015.00452

Castles, A., & Nation, K. (2006). How does orthographic learning happen? In S. Andrews (Ed.), *From inkmarks to ideas: Challenges and controversies about word recognition and reading* (pp. 151–179). https://doi.org/10.4324/9780203841211

Diamanti, V., Goulandris, N., Campbell, R., & Protopapas, A. (2018). Dyslexia profiles across orthographies differing in transparency: an evaluation of theoretical predictions contrasting English and Greek. *Scientific Studies of Reading*, *22*, 55–69. https://doi.org/10.1080/10888438.2017.1338291

Diependaele, K., Morris, J., Serota, R. M., Bertrand, D., & Grainger, J. (2013). Breaking boundaries: Letter transpositions and morphological processing. *Language and Cognitive Processes*, *28*, 988–1003. https://doi.org/10.1080/01690965.2012.719082

Diependaele, K., Ziegler, J. C., & Grainger, J. (2010). Fast phonology and the bimodal interactive activation model. *European Journal of Cognitive Psychology*, *22*, 764–778. https://doi.org/10.1080/09541440902834782

Duñabeitia, J. A., & Carreiras, M. (2011). The relative position priming effect depends on whether letters are vowels or consonants. *Journal of Experimental Psychology: Learning Memory and Cognition*, *37*, 1143–1163. https://doi.org/10.1037/a0023577

Duñabeitia, J. A., Perea, M., & Carreiras, M. (2007). Do transposed-letter similarity effects occur at a morpheme level? Evidence for morpho-orthographic decomposition. *Cognition*, *105*, 691–703. https://doi.org/10.1016/j.cognition.2006.12.001

Ehri, L. C. (2005). Learning to read words: theory, findings and issues. *Scientific Studies of Reading*, *9*, 167–188. https://doi.org/10.1207/s1532799xssr0902

Erdocia, K., Laka, I., Mestres-Missé, A., & Rodriguez-Fornells, A. (2009). Syntactic complexity and ambiguity resolution in a free word order language: behavioral and electrophysiological evidences from Basque. *Brain and Language: A Journal of Clinical, Experimental, and Theoretical Research*, *109*, 1–17. https://doi.org/10.1016/j.bandl.2008.12.003

Frost, R., Kugler, T., Deutsch, A., & Forster, K. I. (2005). Orthographic structure versus morphological structure: Principles of lexical organization in a given language. *Journal of Experimental Psychology: Learning Memory and Cognition*, *31*, 1293–1326. https://doi.org/10.1037/0278-7393.31.6.1293

Germano, G. D., Reilhac, C., Capellini, S. A., & Valdois, S. (2014). The phonological and visual basis of developmental dyslexia in Brazilian Portuguese reading children. *Frontiers in Psychology*, *5*, 1169. https://doi.org/10.3389/fpsyg.2014.01169

Grainger, J., & Beyersmann, E. (2017). Edge-aligned embedded word activation initiates morpho-orthographic segmentation. In B. Ross (Ed.), *Psychology of Learning and*

Motivation (pp. 285–317). https://doi.org/10.1016/bs.plm.2017.03.009

Grainger, J., Colé, P., & Segui, J. (1991). Masked morphological priming in visual word recognition. *Journal of Memory and Language, 30,* 370–384. https://doi.org/10.1016/0749-596X(91)90042-I

Grainger, J., Lété, B., Bertand, D., Dufau, S., & Ziegler, J. C. (2012). Evidence for multiple routes in learning to read. *Cognition, 123,* 280–292. https://doi.org/10.1016/j.cognition.2012.01.003

Grainger, J., & Ziegler, J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology, 2,* 54. https://doi.org/10.3389/fpsyg.2011.00054

Häikiö, T., Bertram, R., & Hyönä, J. (2011). The development of whole-word representations in compound word processing: Evidence from eye fixation patterns of elementary school children. *Applied Psycholinguistics, 32*, 533–551. https://doi.org/10.1017/S0142716411000208

Hasenäcker, J., Beyersmann, E., & Schroeder, S. (2016). Masked morphological priming in German-speaking adults and children: Evidence from response time distributions. *Frontiers in Psychology*, *7*, 929. https://doi.org/10.3389/fpsyg.2016.00929

Hasenäcker, J., Schröter, P., & Schroeder, S. (2017). Investigating developmental trajectories of morphemes as reading units in German. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*, 1093–1108. https://doi.org/10.1037/xlm0000353

Hernández-Cabrera, J. A. (2012). *ULL R Toolbox*. Retrieved from https://sites.google.com/site/ullrtoolbox.

Hyönä, J., Bertram, R., & Pollatsek, A. (2004). Are long compound words identified serially via their constituents? Evidence from an eye-movement-contingent display change study. *Memory & Cognition, 32,* 523–532. https://doi.org/10.3758/BF03195844

Hyönä, J., Yan, M., & Vainio, S. (2018). Morphological structure influences the initial landing position in words during reading Finnish. *The Quarterly Journal of Experimental Psychology*, *71*, 122–130. https://doi.org/10.1080/17470218.2016.1267233

Kuznetsova, A., Bruun Brockhoff, P., & Haubo Bojesen Christensen, R. (2014). *lmerTest: Tests for random and fixed effects for linear mixed effect models (lmer objects of lme4 package).*

Laka, I. (1996). *A brief grammar of Euskara, the Basque language*. Retrieved from http://www.ehu.es/grammar

Laka, I., & Erdocia, K. (2005). Linearization preferences given "Free Word Order"; Subject preferences given ergativity: a look at Basque. In E. Torrego (Ed.), *Of grammar, words, and verses: In honor of Carlos Piera* (Festschrif). Oxford University Press.

Lallier, M., Acha, J., & Carreiras, M. (2016). Cross-linguistic interactions influence reading development in bilinguals: a comparison between early balanced French-Basque and Spanish-Basque bilingual children. *Developmental Science*, *19*, 76–89. https://doi.org/10.1111/desc.12290

Lallier, M., Carreiras, M., Tainturier, M. J., Savill, N., & Thierry, G. (2013). Orthographic transparency modulates the grain size of orthographic processing: behavioral and ERP evidence from bilingualism. *Brain Research*, *1505*, 47–60. https://doi.org/10.1016/j.brainres.2013.02.018

Lallier, M., Valdois, S., Lassus-Sangosse, D., Prado, C., & Kandel, S. (2014). Impact of orthographic transparency on typical and atypical reading development: Evidence in French-Spanish bilingual children. *Research in Developmental Disabilities*, *35*, 1177–1190. https://doi.org/10.1016/j.ridd.2014.01.021

Laudanna, A., Badecker, W., & Caramazza, A. (1992). Processing inflectional and derivational morphology. *Journal of Memory and Language*, *31*, 333–348.

https://doi.org/10.1016/0749-596X(92)90017-R

Law, J. M., Veispak, A., Vanderauwera, J., & Ghesquière, P. (2018). Morphological awareness and visual processing of derivational morphology in high-functioning adults with dyslexia: An avenue to compensation? *Applied Psycholinguistics, 39*, 483–506. https://doi.org/10.1017/S0142716417000467

Lázaro, M., Acha, J., de la Rosa, S., García, S., & Sainz, J. (2017). Exploring the derivative suffix frequency effect in Spanish speaking children. *Reading and Writing: An Interdisciplinary Journal*, *30*, 163–185. https://doi.org/10.1007/s11145-016-9668-2

Lehtonen, A., & Bryant, P. (2005). Active players or just passive bystanders? The role of morphemes in spelling development in a transparent orthography. *Applied Psycholinguistics*, *26*, 137–155. https://doi.org/10.1017/S0142716405050113

Lenth, R. V. (2016). Least-squares means: the {R} package {lsmeans}. *Journal of Statistical Software*, *69*, 1–33. https://doi.org/10.18637/jss.v069.i01

Lobier, M., Peyrin, C., Le Bas, J. F., & Valdois, S. (2012). Pre-orthographic character string processing and parietal cortex: A role for visual attention in reading? *Neuropsychologia*, *50*, 2195–2204. https://doi.org/10.1016/j.neuropsychologia.2012.05.023

Marslen-Wilson, W. D., Bozic, M., & Randall, B. (2008). Early decomposition in visual word recognition: Dissociating morphology, form, and meaning. *Language and Cognitive Processes, 23,* 394–421. https://doi.org/10.1080/01690960701588004

Peereman, R., Sprenger-Charolles, L., & Messaoud-Galusi, S. (2013). The contribution of morphology to the consistency of spelling-to-sound relations: A quantitative analysis based on French elementary school readers. *L'Année Psychologique, 113,* 3–33. https://doi.org/10.4074/S0003503313001012

Perea, M., Marcet, A., & Acha, J. (2017). Does consonant–vowel skeletal structure play a role early in lexical processing? Evidence from masked priming. *Applied*

Psycholinguistics, *39*, 169–186. https://doi.org/10.1017/S0142716417000431

Perea, M., Urkia, M., Davis, C. J., Agirre, A., Laseka, E., & Carreiras, M. (2006). E-Hitz: a word frequency list and a program for deriving psycholinguistic statistics in an agglutinative language (Basque). *Behavior Research Methods*, *38*, 610–615. https://doi.org/10.3758/BF03193893

Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. In L. Verhoeven, C. Elbro, & P. Reitsma (Eds.), *Precursors of functional literacy* (pp. 189–213). Amsterdam: John Benjamins.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review*, *114*, 273–315. https://doi.org/10.1037/0033-295X.114.2.273

Quémart, P., Casalis, S., & Colé, P. (2011). The role of form and meaning in the processing of written morphology: A priming study in French developing readers. *Journal of Experimental Child Psychology*, *109*, 478–496. https://doi.org/10.1016/j.jecp.2011.02.008

Quémart, P., Casalis, S., & Duncan, L. G. (2012). Exploring the role of bases and suffixes when reading familiar and unfamiliar words: evidence from French young readers. *Scientific Studies of Reading*, *16*, 424–442. https://doi.org/10.1080/10888438.2011.584333

Rastle, K. (2018). The place of morphology in learning to read in English. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior*. https://doi.org/10.1016/j.cortex.2018.02.008

Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin & Review*, *11*, 1090–1098. https://doi.org/10.3758/BF03196742

Suárez-Coalla, P., Martínez-García, C., & Cuetos, F. (2017). Morpheme-based reading and writing in Spanish children with dyslexia. *Frontiers in Psychology*, *8*, 1952. https://doi.org/10.3389/fpsyg.2017.01952

Taft, M., & Forster, K. I. (1975). Lexical storage and retrieval of prefixed words. *Journal of Verbal Learning and Verbal Behavior*, *14*, 638–647. https://doi.org/10.1016/S0022-5371(75)80051-X

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

Taft, M., & Nguyen-Hoan, M. (2010). A sticky stick? The locus of morphological representation in the lexicon. *Language and Cognitive Processes*, *25*, 277–296. https://doi.org/10.1080/01690960903043261

Traficante, D., Marcolini, S., Luci, A., Zoccolotti, P., & Burani, C. (2011). How do roots and suffixes influence reading of pseudowords: A study of young Italian readers with and without dyslexia. *Language and Cognitive Processes*, *26*, 777–793. https://doi.org/10.1080/01690965.2010.496553

van den Boer, M., van Bergen, E., & de Jong, P. F. (2015). The specific relation of visual attention span with reading and spelling in Dutch. *Learning and Individual Differences: Journal of Psychology and Education*, *39*, 141–149. https://doi.org/10.1016/j.lindif.2015.03.017

Verhoeven, L., & Schreuder, R. (2011). Morpheme frequency effects in Dutch complex word reading: A developmental perspective. *Applied Psycholinguistics*, *32*, 483–498. https://doi.org/10.1017/S0142716411000178

Wechsler, D. (2003). *Wechsler intelligence scale for children--Fourth Edition*. San Antonio, TX: The Psychological Corporation.

Yan, M., Zhou, W., Shu, H., Yusupu, R., Miao, D., Krügel, A., & Kliegl, R. (2014). Eye movements guided by morphological structure: Evidence from Uighur language. *Cognition*, *132*, 181–215. https://doi.org/10.1016/j.cognition.2014.03.008

Footnotes

[1] A pseudoword condition with a stem and suffix (+stem+suffix) was excluded because few pseudowords of this type could be created while also controlling for letter repetition (see Methods).

[2] A word on Basque orthotactics: Basque has a five vowel system (the same as Spanish), five diphthongs, twenty-four consonants and the following digraphs: dd, ll, rr, ts, tt, tx, tz. Few consonants form consonant clusters. Letters of the Spanish alphabet are used, with C, Q, V, W and Y only used in foreign words/expressions. Main differences between Spanish and Basque orthography is the use of "K" for /k/ in Basque and the consonant clusters ts, tz, tx. Regarding phonology, Spanish and Basque share many similarities with some extra phonemes in Basque (e.g., Larraza, Samuel, & Onederra, 2016). Basque syllable structure follows the (C)(C)V(C)(C) pattern and the vowel is the syllable nucleus.

[3] Repetition was used for both stems and suffixes because usually only suffixes are used repeatedly.

[4] Sensitivity on simple pseudowords reflects the average across twice as many datapoints as in the other conditions.

[5] One item was removed from the analysis (included in the target-absent trials of the +stem-suffix pseudowords) because the stem had been mistakenly removed (the included pseudoword was "**ige**atxu" instead of "**ile**atxu").

Table 1

Descriptive statistics on control variables for the 30 fourth grade children

	Mean *(SD)*	Median	Range
Chronological Age (years)	9.93 *(0.30)*	10	9.5 – 10.5
Non-verbal intelligence (age-standardised)	11.90 *(2.88)*	12.5	7 – 16
Single Letter Processing (% overall score[a])	95 *(4)*	96	82 – 99
Single Letter Processing (weighted score[b])	13.96 *(0.89)*	14.25	11.54 – 14.96[c]
VA Span[d] (average *d'*)	1.13 *(0.58)*	0.99	0.25 – 2.33

Note. [a] average % performance across all presentation durations. [b] score at 33 ms * 5 + score at 50 ms * 4 + score at 67 ms * 3 + score at 84 ms * 2 + score at 101 ms, [c] The possible values range from 0 to 15. [d] Visual Attention Span

Table 2

Descriptive statistics on sensitivity scores on morphological visual one-back task

Pseudoword condition and sub-condition			Sensitivity scores (*d'*) by position		
			1	4	7
Morphologically Simple	*-stem -suffix*	*M (SD)*	1.83 *(1.22)*	1.54 *(0.93)*	1.24 *(1.05)*
		Median	1.82	1.45	1.1
		Range	-0.28 – 4.65	0.02 – 3.69	-0.43 – 4.06
Morphologically Complex	*All items*	*M (SD)*	1.81 *(1.01)*	1.52 *(0.91)*	1.25 *(0.81)*
		Median	1.9	1.64	1.16
		Range	-0.1 – 3.89	0 – 3	-0.18 – 2.8
	+ stem -suffix	*M (SD)*	1.97 *(1.1)*	1.48 *(0.89)*	1.37 *(0.88)*
		Median	1.84	1.28	1.18
		Range	-0.6 – 3.89	0.18 – 3.71	-0.04 – 3.71
	- stem +suffix	*M (SD)*	1.81 *(1.06)*	1.77 *(1.3)*	1.27 *(0.97)*
		Median	1.85	1.81	1.3
		Range	0.05 – 3.92	-0.42 – 3.89	-0.39 – 3.29

Table 3

Results from the linear mixed model with performance on the morphological one-back task as the outcome variable and -stem +suffix pseudowords as the reference level condition (total of 90 datapoints, 30 participants)

		Random Effects		
Group	Name	Variance	*SD*	
Subject	Intercept	0.41	0.64	
Residuals		0.19	0.44	

	Fixed Effects		
Group	*β*	*SE*	*p*
Intercept	1.62	0.14	<.001
Chronological Age	0.60	0.48	.22
Non-verbal intelligence	0.03	0.05	.49
Single Letter Processing	0.35	0.16	.04
VA span	0.62	0.28	.03
-stem -suffix condition	-0.08	0.11	.48
+stem -suffix condition	-0.01	0.11	.90
VA span:-stem -suffix condition	-0.08	0.20	.67
VA span:+stem -suffix condition	-0.55	0.20	.008

Figure Captions

Fig 1. Morphological visual one-back paradigm.

Fig 2. Target position effect in the morphological visual one-back task (morphologically complex pseudowords include both +stem-suffix and -stem+suffix items).

Fig 3. Target Position by Morphological Structure interaction in the morphological visual one-back task.

Fig 4. VA span skills (centred values) and average performance on the morphological visual one-back task for each type of pseudoword. Points represent by subject average performance by condition, lines reflect regression lines by condition. Control variables are not accounted for in the plot.

Appendix A

Table A1

Morphologically complex pseudowords used in the morphological visual one-back task

Pseudoword	Sub-condition	Target	Trial Type	Pseudoword	Sub-condition	Target	Trial Type	Pseudoword	Sub-condition	Target	Trial Type
AHOIDER	+stem-suffix	A	Present	ADEZKOI	-stem+suffix	A	Present	IGONEZU	+stem-suffix	A	Absent
ATEOSDU	+stem-suffix	A	Present	ARTUKOI	-stem+suffix	A	Present	OINTZUK	+stem-suffix	A	Absent
AHOILUS	+stem-suffix	A	Present	AMLITXO	-stem+suffix	A	Present	IGOREMU	+stem-suffix	A	Absent
ATEOZPU	+stem-suffix	A	Present	ABNITXO	-stem+suffix	A	Present	OINESPU	+stem-suffix	A	Absent
IGOARFU	+stem-suffix	A	Present	UZFAKOI	-stem+suffix	A	Present	IGOSPRU	+stem-suffix	A	Absent
OINAKRE	+stem-suffix	A	Present	BENAKOI	-stem+suffix	A	Present	OINUTEL	+stem-suffix	A	Absent
IGOABLU	+stem-suffix	A	Present	ZUKATXO	-stem+suffix	A	Present	AHOSDUM	+stem-suffix	I	Absent
OINAPLE	+stem-suffix	A	Present	URDATXO	-stem+suffix	A	Present	OHEALZU	+stem-suffix	I	Absent
IGOFEMA	+stem-suffix	A	Present	TSUNERA	-stem+suffix	A	Present	AHODUTZ	+stem-suffix	I	Absent
OINUSTA	+stem-suffix	A	Present	PEMOTZA	-stem+suffix	A	Present	OHEASFU	+stem-suffix	I	Absent
IGOLDUA	+stem-suffix	A	Present	GULMERA	-stem+suffix	A	Present	AHOGUDE	+stem-suffix	I	Absent
OINRUXA	+stem-suffix	A	Present	BRUOTZA	-stem+suffix	A	Present	OHEAFLU	+stem-suffix	I	Absent
IGOSKEN	+stem-suffix	I	Present	IMDEARO	-stem+suffix	I	Present	ATEIZKU	+stem-suffix	O	Absent
ILEOFUZ	+stem-suffix	I	Present	IGUXARO	-stem+suffix	I	Present	ILEASMU	+stem-suffix	O	Absent
IGORTEZ	+stem-suffix	I	Present	ISTOERA	-stem+suffix	I	Present	ATEIRMU	+stem-suffix	O	Absent
ILEOSKU	+stem-suffix	I	Present	IZKOERA	-stem+suffix	I	Present	ILEATRU	+stem-suffix	O	Absent
OHEIPZU	+stem-suffix	I	Present	GUDIARO	-stem+suffix	I	Present	ATEIZDU	+stem-suffix	O	Absent
AHOILER	+stem-suffix	I	Present	FULIARO	-stem+suffix	I	Present	IGEATXU*	+stem-suffix	O	Absent
OHEIZFU	+stem-suffix	I	Present	UXTIERA	-stem+suffix	I	Present	UGNEKOI	-stem+suffix	A	Absent
AHOIKEL	+stem-suffix	I	Present	GUPIERA	-stem+suffix	I	Present	GEFUKOI	-stem+suffix	A	Absent
OHERTAI	+stem-suffix	I	Present	PERAKOI	-stem+suffix	I	Present	TZENKOI	-stem+suffix	A	Absent
AHOMEFI	+stem-suffix	I	Present	STRUGAI	-stem+suffix	I	Present	USNETXO	-stem+suffix	A	Absent
OHEGUZI	+stem-suffix	I	Present	ERTAKOI	-stem+suffix	I	Present	BUERTXO	-stem+suffix	A	Absent
AHOGELI	+stem-suffix	I	Present	EZDUGAI	-stem+suffix	I	Present	ULGITXO	-stem+suffix	A	Absent
OINARLE	+stem-suffix	O	Present	OLPEGAI	-stem+suffix	O	Present	EZPUARO	-stem+suffix	I	Absent
OHEIFUN	+stem-suffix	O	Present	OFENGAI	-stem+suffix	O	Present	UXEDARO	-stem+suffix	I	Absent
OINAMRU	+stem-suffix	O	Present	OKLITZA	-stem+suffix	O	Present	FETKARO	-stem+suffix	I	Absent
OHEIDUZ	+stem-suffix	O	Present	OSRITZA	-stem+suffix	O	Present	ULNOERA	-stem+suffix	I	Absent
ILEOSNU	+stem-suffix	O	Present	URFOGAI	-stem+suffix	O	Present	GLUOERA	-stem+suffix	I	Absent
ATEOMUN	+stem-suffix	O	Present	ELMOGAI	-stem+suffix	O	Present	LUPOERA	-stem+suffix	I	Absent
ILEONDU	+stem-suffix	O	Present	URGOTZA	-stem+suffix	O	Present	URKEGAI	-stem+suffix	O	Absent
ATEORUF	+stem-suffix	O	Present	EKPOTZA	-stem+suffix	O	Present	URENGAI	-stem+suffix	O	Absent
ILEAGNO	+stem-suffix	O	Present	UZENARO	-stem+suffix	O	Present	ZUDEGAI	-stem+suffix	O	Absent
ATEMUDO	+stem-suffix	O	Present	ERMATXO	-stem+suffix	O	Present	URPETZA	-stem+suffix	O	Absent
ILEATRO	+stem-suffix	O	Present	UKENARO	-stem+suffix	O	Present	ELSITZA	-stem+suffix	O	Absent
ATEKUBO	+stem-suffix	O	Present	ULFATXO	-stem+suffix	O	Present	EFRITZA	-stem+suffix	O	Absent

[*] The stimulus that was removed from the analysis due to the incorrect substitution of the stem *“ile”* by *“ige”*.

Table A2

Morphologically simple pseudowords used in the morphological visual one-back task

Pseudoword	Target	Trial Type	Pseudoword	Target	Trial Type	Pseudoword	Target	Trial Type
AZMIERU	A	Present	ULTIZRO	I	Present	BITEZON	A	Absent
AGUISON	A	Present	BUNIFTO	I	Present	UZTIFEN	A	Absent
AKEIZGU	A	Present	PEGINOA	I	Present	BIMEOLU	A	Absent
ATSOELU	A	Present	TUHIMOA	I	Present	USTEODI	A	Absent
ATXODEI	A	Present	OSTEFRI	I	Present	IFENUTO	A	Absent
ARUKEXI	A	Present	OGERADI	I	Present	ISEDOKU	A	Absent
AHELUZO	A	Present	AGOSEMI	I	Present	OLIUREN	A	Absent
ARENUXO	A	Present	AXETUNI	I	Present	OLDIFER	A	Absent
ILKASFE	A	Present	ENDOALI	I	Present	PUKOREI	A	Absent
ISUARON	A	Present	ZENOAGI	I	Present	BOSUNEI	A	Absent
OGDAINE	A	Present	UKOAGDI	I	Present	IGRUSTO	A	Absent
ONEARUZ	A	Present	UHEALTI	I	Present	IRETUNO	A	Absent
EMOATSI	A	Present	ORGIKUN	O	Present	UNAORDE	I	Absent
GEOARXI	A	Present	OHLIGAZ	O	Present	EDRONAU	I	Absent
ULEARGO	A	Present	ODUALTE	O	Present	USKERAO	I	Absent
ENBATLO	A	Present	OLEASRI	O	Present	PURATZO	I	Absent
IBOGURA	A	Present	OTESURI	O	Present	ORUTAGE	I	Absent
IRDUNEA	A	Present	OPELATI	O	Present	OFUZAME	I	Absent
OLKURZA	A	Present	OTUNKEA	O	Present	APTOLEN	I	Absent
OIPUXKA	A	Present	OIZENBA	O	Present	AMNOEKU	I	Absent
PUFIEKA	A	Present	ILDOASE	O	Present	URLANTO	I	Absent
UZGITSA	A	Present	ISKOEGU	O	Present	GETORAU	I	Absent
FIDOGNA	A	Present	ALFOKER	O	Present	OFRUSEA	I	Absent
UTXOSRA	A	Present	ASLOTZU	O	Present	OBEFUGA	I	Absent
IRLOMTU	I	Present	BINOZLE	O	Present	AHRISTU	O	Absent
IKTOLMU	I	Present	UNDOERI	O	Present	AGNIDRE	O	Absent
IPSALDU	I	Present	UTSODIA	O	Present	TURAZNI	O	Absent
IFRATUN	I	Present	ENTOILA	O	Present	URMANTI	O	Absent
ITENAKO	I	Present	IHUNEDO	O	Present	IKRUEPA	O	Absent
ILUZAXO	I	Present	ILTUAMO	O	Present	URBEIMA	O	Absent
IRNETUA	I	Present	AZEDUFO	O	Present	ABRIMEN	O	Absent
IHESLUA	I	Present	AMUENDO	O	Present	AFEIGRU	O	Absent
OGNIAZU	I	Present	PIDUTAO	O	Present	ESMAIZU	O	Absent
ORLIENU	I	Present	ULPIZAO	O	Present	EHUAZBI	O	Absent
ALEIKZU	I	Present	GINATEO	O	Present	EZBUNIA	O	Absent
ARZINUK	I	Present	USPAMLO	O	Present	ITXELKA	O	Absent

Table A3

Information on the stems and suffixes used

Morphemes	Meaning and examples	Frequency
Stems		
Igo	igo = climb, go up igo + aldi (time, phase, season) = climb (noun) igo + gailu (device) = lift/elevator	175.31
Ate	ate = door ate + zain (person of occupation related to the noun) = doorman ate+ gi = doorway	132.49
Ile	ile = hair ile + dun (someone who has/is) = hairy, ile + di = mane	87.15
Aho	aho = mouth aho + pe = secret aho + bero (hot/heat) = charlatan	89
Ohe	ohe = bed ohe + kide (companion, member) = lover ohe + buru (head) = headboard	68.75
Oin	oin = foot oin + alde (zone, side, towards) = base, foot of page/bed oin + uts = barefoot	41.02
Suffixes		
Koi	apt or devoted to eliz (eliza = church) + koi = religious bere (possessive, yours, his) + koi=selfish	2.66
Gai	able to, disposed to do something andre (woman) + gai = girlfriend elika (related to nutrition) + gai = food	391.56
Txo	diminutive suffix: dama (woman) + txo = damsel errege (king) + txo = kinglet	5.68
Tza	lagun (companion, friend) + tza = help (noun) nagusi (boss, superior) + tza = superiority	0.48
Era	gai + era = height konta (kontatu = narrate) + era = story	395.3
Aro	manner or time or season mait (maite = person who is loved, dear) + aro = lovingly gazt (gazte= young person) + aro = youth (the time)	62.11

Table A4

Descriptive statistics on accuracy scores on morphological visual one-back task

Pseudoword condition and sub-condition			Percent (%) correctly identified letters by position and on absent trials*			
			Absent	1	4	7
Morphologically Simple	-stem -suffix	*M (SD)*	70 (20)	78 (17)	73 (19)	64 (23)
		Median	72	79	75	69
		Range	25 – 94	42 – 100	8 – 96	12 – 96
Morphologically Complex	All items	*M (SD)*	69 (19)	80 (12)	73 (20)	66 (20)
		Median	71	83	81	73
		Range	29 – 94	52 – 100	25 – 96	21– 96
	+ stem -suffix	*M (SD)*	71 (18)	80 (15)	70 (23)	67 (23)
		Median	76	83	75	75
		Range	24 – 100	42 – 100	17 – 92	17 – 100
	- stem +suffix	*M (SD)*	67 (22)	80 (13)	77 (22)	66 (22)
		Median	67	83	83	71
		Range	28 – 100	50 – 100	25 – 100	17 – 100

* In our case children had 67% probability of being accurate responding positively. Nevertheless, it has been suggested that the higher the probability of giving a specific type of answer, the more likely people are to underestimate the chance level (Lee & Danileiko, 2014).

Table A5

Results from the linear mixed model analysis when the reference is changed to either -stem -suffix or +stem - suffix (total of 90 datapoints, 30 participants)

a)

		Random Effects		
Group	Name	Variance	*SD*	
Subject	Intercept	0.41	0.64	
Residuals		0.19	0.44	
		Fixed Effects		
Group		β	*SE*	*p*
Intercept		1.54	0.14	<.001
Chronological Age		0.60	0.48	.22
Non-verbal intelligence		0.03	0.05	.49
Single Letter Processing		0.35	0.16	.04
VA span		0.53	0.28	.06
-stem +suffix condition		0.08	0.11	.48
+stem -suffix condition		0.07	0.11	.56
VA span:-stem +suffix condition		0.08	0.20	.67
VA span:+stem -suffix condition		-0.46	0.20	.02

b)

		Random Effects		
Group	Name	Variance	*SD*	
Subject	Intercept	0.41	0.64	
Residuals		0.19	0.44	
		Fixed Effects		
Group		β	*SE*	*p*
Intercept		1.60	0.14	<.001
Chronological Age		0.60	0.48	.22
Non-verbal intelligence		0.03	0.05	.49
Single Letter Processing		0.35	0.16	.04
VA span		0.07	0.28	.81
-stem -suffix condition		-0.07	0.11	.56
+stem -suffix condition		0.01	0.11	.90
VA span:-stem -suffix condition		0.46	0.20	.02
VA span:+stem -suffix condition		0.55	0.20	.008

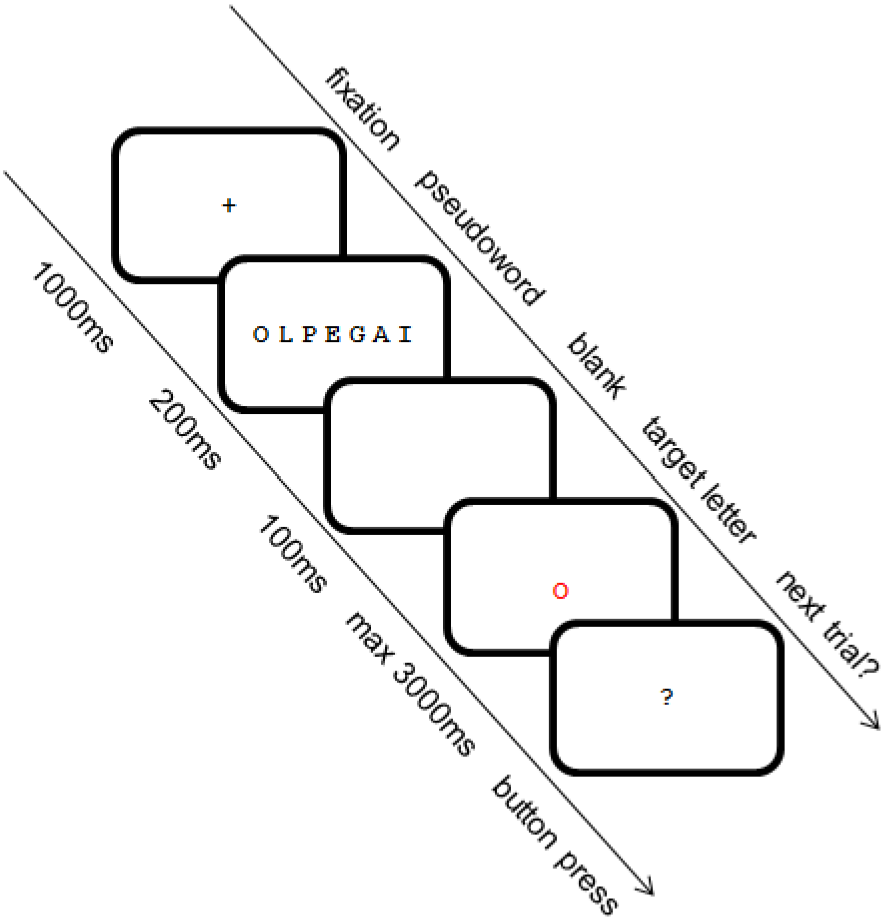
fixation
pseudoword
blank
target letter
next trial?
+
OLPEGAI
O
?
1000ms
200ms
100ms
max 3000ms
button press

Figure 1.

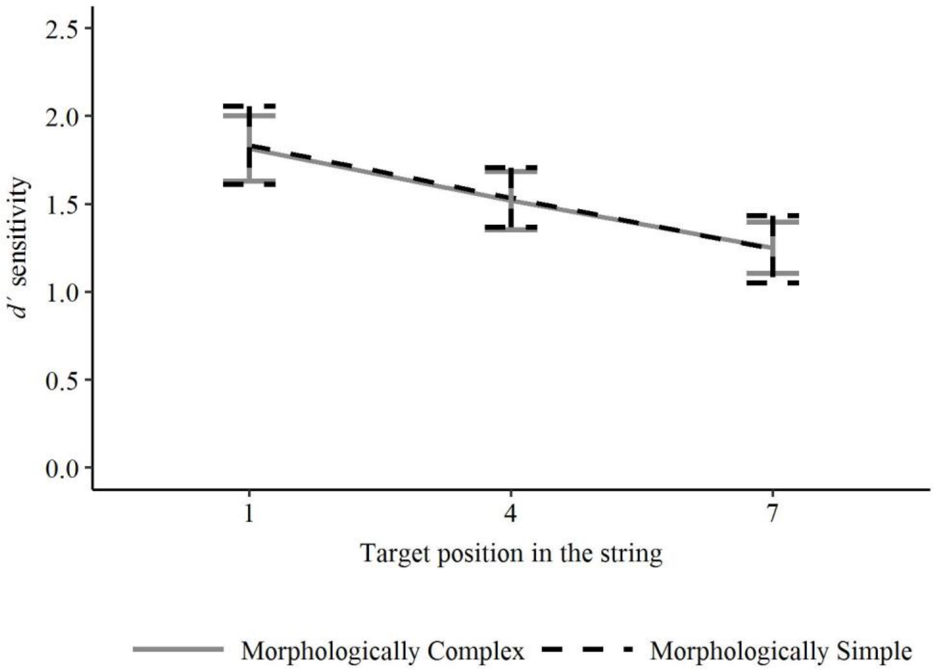
2.5
2.0
1.5
1.0
0.5
0.0
d′ sensitivity
1
4
7
Target position in the string
Morphologically Complex
Morphologically Simple

Figure 2.

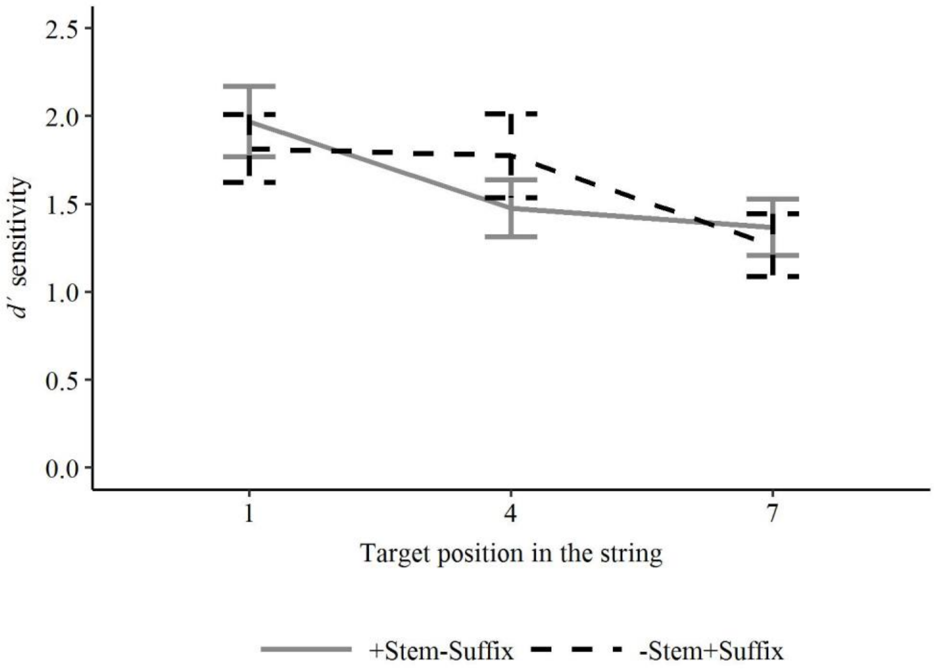
2.5
2.0
1.5
1.0
0.5
0.0
d′ sensitivity
1
4
7
Target position in the string
+Stem-Suffix
-Stem+Suffix

Figure 3.

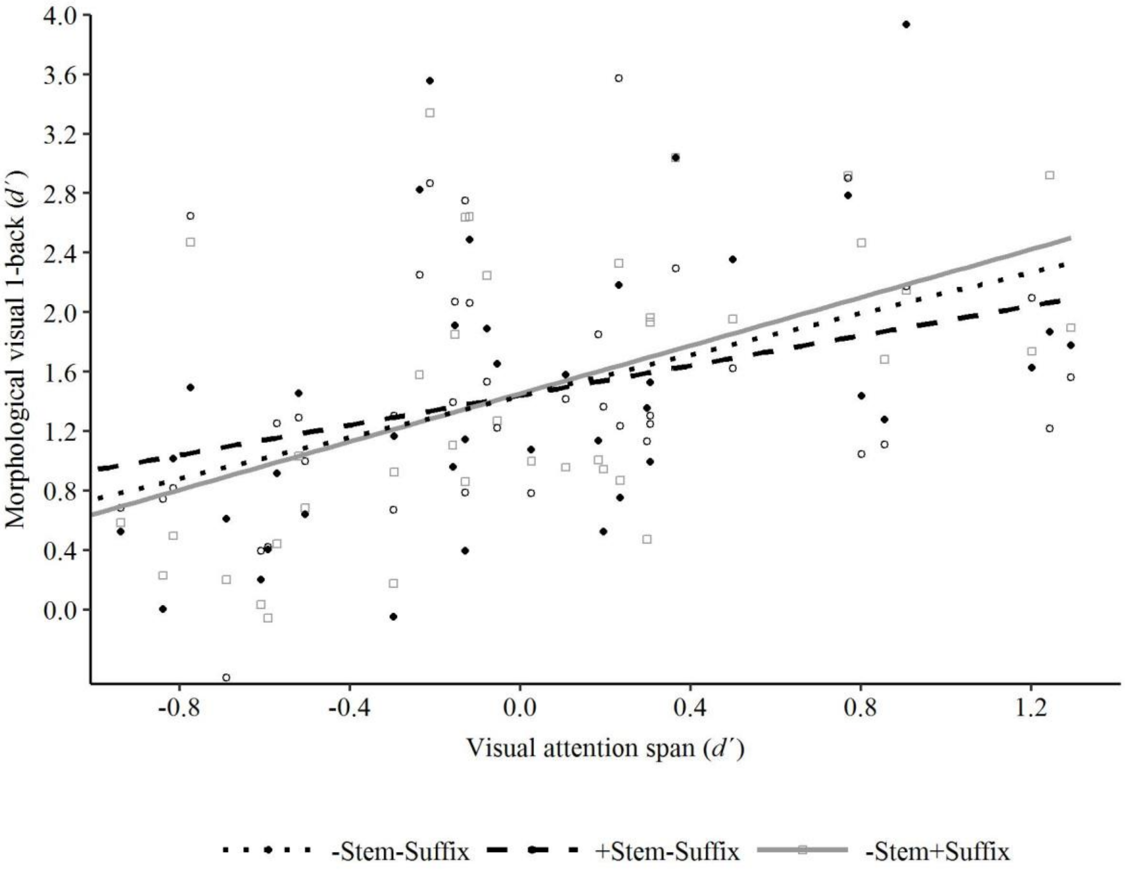
Morphological visual 1-back (d')
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
-0.8
-0.4
0.0
0.4
0.8
1.2
Visual attention span (d')
-Stem-Suffix
+Stem-Suffix
-Stem+Suffix

Figure 4.

Supplementary Material

Additional exploratory analyses

In the manuscript it is briefly mentioned that an open question in the literature on morphological processing is whether the effects of morphemes on reading are particularly linked to the semantic properties of the morphemes themselves or an exclusive result of the internalization of frequently encountered orthographic combinations (also see:Amenta & Crepaldi, 2012). Most of the studies that are presented in the introduction -particularly those in developing readers-do not directly address this question and certain studies that have addressed the question yield inconsistent results (e.g., in spelling: Deacon et al., 2008; Deacon & Leung, 2013; in masked priming: Andoni Duñabeitia, Perea, & Carreiras, 2008; Duñabeitia et al., 2011; Longtin, Segui, & Hallé, 2003; Rastle et al., 2004). While we consider that any effect of morphemes in the morphological visual one-back task is likely to arise due to the internalization of these recurrent orthographic regularities this does not necessarily depend on their status as meaningful units. Indeed in a morphological rich and transparent orthography such as Basque morphemes are not only very frequent but also particularly stable in their form. Thus sensitivity to these units and modulation of visual attention distribution could arise based on the frequency of the orthographic units entirely. Our study is not designed to test this hypothesis since in our stimuli the presence of a real morpheme is confounded with higher frequency of the orthographic unit in the position of the pseudoword in which the real morpheme appears (i.e., the first three letters for the stems and the last three letters for the suffixes). Nevertheless we explore whether our results were driven by the frequency of the orthographic units constituting the real stems and suffixes or by their morphological nature with an exploratory analysis controlling for the frequency of the orthographic units.

To control for the frequency of the orthographic stimuli, position-sensitive bigram and trigram frequencies were calculated based on the E-Hitz database (Perea et al., 2006; see Supplementary Tables S1 and S2). Larger differences were observed on bigram/trigram frequencies corresponding to the final three letters of the pseudowords, particularly for morphologically complex pseudowords with a real suffix (-stem+suffix). Controlling for initial and final trigram frequencies of each pseudoword was considered to provide the most direct manner of controlling for the frequency of the three letter stems and suffixes included in the stimuli.

Generalized mixed-effect models for binomially distributed outcomes including subjects and items as crossed random effects (Baayen, Davidson, & Bates, 2008; lme4 package: Bates, Mächler, Bolker, & Walker, 2015; Jaeger, 2008) were used to analyse accuracy on each pseudoword while controlling for initial/final trigram frequency measures of the pseudoword. Accuracy scores were preferred over *d'* sensitivity scores in this analysis since calculation of the latter requires averaging across conditions. P values were computed based on the normal approximation. Only trials in which the target letter was present were analysed and Target Position (first, fourth, seventh) was included as a categorical factor in the analysis. Participants with below 50% accuracy on trials in which the target was absent (five participants) were removed from the analysis since they were highly biased towards responding that the target was present, and their responses could be unreliable (this was accounted for by *d´* scores and thus these participants were not removed in the ANOVA analyses). Firstly all the stimuli were analysed together -investigating effects of Morphological Complexity- and then analyses included only the morphologically complex stimuli to focus on Morphological Structure (presence of a real stem or a real suffix). All effects (Morphological Complexity, Morphological Structure and Target Position) were included as categorical factors in the analyses and were coded as treatment contrasts (the default).

Results

For each set of analyses, we fit one model including initial and final trigram *type* frequencies (reflecting the number of words included in the database that contain the specific orthographic unit in that position and thus its combinability with different units) and another including initial/final trigram *token* frequencies (reflecting the frequency of all the words in the database containing the specific orthographic unit in that position and thus the frequency with which these orthographic units are encountered in written language). These measures were not normally distributed so we improved their distribution as much as possible by shifting scores to a positive range, applying a square root transform to type frequencies and a log transform to token frequencies. Values were also mean-centred.

Correlations between initial/final trigram frequencies were moderate across all stimuli (type: $r = -0.31$, $p < .001$; token: $r = -0.30$, $p < .001$) and high-as expected based on stimulus creation (items with a real stem did not have a real suffix and vice versa)-across the morphologically complex stimuli (type: $r = -0.59$, $p < .001$; token: $r = -0.60$, $p < .001$). Given the collinearity, particularly in the case of morphologically complex stimuli, any effect of initial/final token or type frequency was evaluated when the other continuous variable was removed from the analysis (e.g., testing that a significant effect of trigram initial type frequency was still observed when final trigram type frequency was not included in the model). If this was not the case it is reported in the analyses.

Analysis across all pseudowords. When analysing all the items (see Supplementary Table S3a for the model results), accuracy on letters appearing at the first position of morphologically simple stimuli was the reference level. When controlling for initial/final trigram type frequencies, accuracy for targets appearing in the seventh position was lower than for those appearing in the first position (Intercept = 1.66, β = -1.02, *SE* = 0.29, *p* < .001). Relevelling so the performance on the fourth position was the reference level showed that accuracy for targets appearing in the seventh position was also significantly lower than for those appearing in the fourth position (Intercept = 1.21, β = -0.55, *SE* = 0.22, *p* = .01). Similar effects were observed when controlling for initial/final trigram token frequencies (see Supplementary Table S3b for the model results). Moreover in this model, higher final trigram token frequencies were also linked to more accurate responses (β = 0.03, *SE* = 0.01, *p* = .04).

This analyses demonstrated that when controlling for initial/final trigram type and token frequencies differences between letter identification performance on the first and fourth positions were not significant -whilst in the initial ANOVA with all items a pattern of left to right decrease in performance (first>fourth>seventh) was found. This could result from the observed significant final trigram token frequency effect on accuracy.

Analysis of morphologically complex pseudowords. When analysing only morphologically complex items (see Supplementary Table S4a for the model results) accuracy on target letters appearing at the first position of the pseudowords with a real stem (+stem-suffix) was set as the reference level. The results of the model controlling for initial/final trigram type frequencies indicated that accuracy on targets appearing in the fourth (Intercept = 1.87, β = -0.66, *SE* = 0.33, *p* = .047) and seventh positions (β = -0.81, *SE* = 0.29, *p* = .005) was significantly lower than on the first position for pseudowords including a real stem (+stem-suffix). Relevelling so that performance on the fourth position was the reference also indicated that accuracy on the fourth and seventh positions did not differ significantly for the pseudowords with a real stem (+stem-suffix, Intercept = 1.23, β = -0.17, *SE* = 0.26, *p* = .52). For the pseudowords with a pseudo-stem (-stem+suffix), the significant difference between accuracy on targets appearing in the first and as compared to the fourth position was not observed as indicated by the interaction (Position (fourth): Morphological Structure (-

stem+suffix): Intercept = 1.23, β = 0.66, *SE* = 0.31, *p* = .03). Moreover, for the pseudowords with a pseudo-stem (-stem+suffix) the difference between accuracy on the fourth and seventh positions -lower accuracy on seventh position- *was* significant (reference level set to accuracy on the fourth position for -stem+suffix items: Intercept= 1.53, β = -0.91, *SE* = 0.27, *p* < .001). Moreover, higher initial trigram type frequency was related to lower overall accuracy (Intercept = 1.23, β = -0.13, *SE* = 0.06, *p* = .04). Similar patterns of results were observed when including initial/final trigram token frequency in the model. In this model by item random effects had to be removed due to singularity errors. However when controlling for initial/final trigram token frequencies, the difference in performance on the first and fourth position for the pseudowords with a real stem (+stem-suffix) was marginal rather than significant (Intercept = 1.85, β = -0.58, *SE* = 0.33, *p* = .08). Similarly the interaction indicating this difference between first and fourth position shows a significantly different pattern in the pseudowords with a pseudo-stem was also marginal (Position (fourth): Morphological Structure (-stem+suffix): β = 0.59, SE = 0.31, *p* = 0.057).

We highlight that differences between the observed effects in the initial ANOVA analysis across morphologically complex items and the analyses controlling for initial/final trigram type and token frequencies were observed only when controlling for trigram token frequencies. Specifically, for pseudowords with a real stem (+stem-suffix) the post hoc comparisons following the ANOVA analysis indicated performance on the first position was significantly better than on both the fourth and seventh positions, that in turn did not differ between them (first>fourth=seventh). However, when controlling for trigram token frequency the difference between performance on the first and fourth positions was marginal (while all other effects remained the same). Since in the latter analysis, higher final position trigram token frequency was linked to higher average accuracy (β = 0.05, *SE* = 0.02, *p* = .03) it could be argued that the frequency of the structures linked to token values, rather than their morphological nature, were contributing to the observed effects. We will return to this in the discussion of these exploratory results.

Discussion of the results of the exploratory analyses

In the supplementary section of the manuscript we aimed to address the question of whether the observed effects of morphemes were driven by the frequency of their orthographic units or could be attributed to their status as meaningful units. Indeed, the timing of the morphological visual one-back task and the absence of a “morphological benefit” in performance suggest effects might be driven by orthographic regularities. We considered that if effects were due to the frequency of the orthographic units, they would be eliminated when controlling for these measures. Controlling for trigram token frequencies is likely to be the best test of this hypothesis since they most closely reflect the frequency with which these orthographic units are encountered in written language.

The results of the exploratory regression analyses provide partial support for the effect of morphemes being driven by the frequency of their orthographic units. Overall, the analyses strongly suggest that trigram frequencies can influence the distribution of attention across the pseudoword. More specifically, when controlling for either type or token trigram frequencies in the analysis across all items, the pattern of better performance on the initial than on the central position was no longer observed (meaning performance followed the pattern observed in the items with a real suffix: first=fourth>seventh). Moreover, both across all items and for morphologically complex items, higher final trigram token frequency was linked to higher accuracy. These patterns suggest that the pattern of distribution of visual attention we attributed to the presence of the morphemes might be related to the token frequency of the orthographic unit (particularly that of the final trigram of the pseudoword). Nevertheless, when controlling for trigram token frequencies the pattern of performance remained the same for the items with a pseudo-stem (that include a real suffix: first=fourth>seventh) and the pattern of significance was only partly modulated for the items with a real stem for which the difference between performance on the initial and central positions was no longer significant but marginal. This suggests that similar distribution of attention across the initial and central positions is likely to be observed either due to the presence of a real suffix or even of a highly frequent pseudo-suffix. Regarding the effect of the initial trigram only an effect of higher initial trigram type frequency leading to lower accuracy was observed. Yet, controlling for this measure did not modulate the observed effects and could be reflecting the pattern observed for pseudowords with a real stem (that indeed tend to also show higher initial trigram type frequency).

Importantly, the exploratory analyses support: a) that after controlling for initial and final trigram frequencies, the effects or morphological structure remained either significant or marginal suggesting they cannot be entirely attributed to the frequency of the orthographic units, and b) that the presence of highly frequent orthographic units at the end of the pseudoword indeed leads to similar patterns of performance as the presence of a real suffix. This suggests that the patterns observed (particularly those attributed to the presence of a real suffix) are likely to be partly but not entirely driven by the frequency of the orthographic regularities. This could suggest there are additive effects: while the frequency with which morphemes appear in written language improves their internalization and development of orthographic knowledge, their status as meaningful units further boosts this process (in line with the lexical quality hypothesis: Perfetti & Hart, 2002). Yet, it must be noted that our stimuli were constructed in a way in which these two aspects (morpheme presence and trigram frequency) overlap. Future studies should attempt to manipulate morpheme presence and orthographic unit frequency orthogonally across conditions to shed new light on the present results.

The exploratory analyses also support that the effect of suffixes might be more robust than that of stems when investigating early visuo-orthographic processing. Specifically, the observed effects of final trigram token frequencies in both the analysis across all pseudowords and only on morphologically complex pseudowords suggest that the frequency of these orthographic units has robust effects in the morphological visual one-back task. This could also be in line with two other observations based on prior research. On the one hand, it is in line with theories suggesting suffixes are processed early through affix stripping or chunking (Grainger & Ziegler, 2011; Taft & Forster, 1975). On the other hand it also aligns with the observation that while both stems and suffixes influence processing, stems might have a more prominent role in naming while suffixes do so in lexical decision (the latter being a task more finely tuned to observe effects of visuo-orthographic processing, Casalis, Quémart, & Duncan, 2015; Quémart, Casalis, & Duncan, 2012; Traficante, Marcolini, Luci, Zoccolotti, & Burani, 2011).

Supplementary Table S1

Descriptives on bigram type and token frequencies for morphologically complex (+stem-suffix and -stem+suffix) and morphologically simple (-stem-suffix) pseudoword stimuli. It should be noted that differences are particularly observed in the fifth and sixth bigram positions when a real suffix is present. Frequencies were extracted based on all the seven-letter words included in the E-Hitz database (Perea et al., 2006).

		Bigram Position					
		1	2	3	4	5	6
Type Frequency							
Complex (all)	*M (SD)*	56.39 (50.33)	48.69 (59.83)	51.70 (51.70)	95.35 (99.68)	105.34 (106.74)	88.38 (150.71)
	Range	1 - 290	0 - 337	0 - 275	1 - 383	0 - 347	0 - 948
+stem-suffix	*M (SD)*	50.67 (15.48)	64.20 (58.76)	35.37 (42.51)	86.07 (101.20)	36.02 (62.17)	55.93 (135.86)
	Range	34 - 78	14 - 188	0 - 224	1 - 383	0 - 315	0 - 948
-stem+suffix	*M (SD)*	62.11 (69.33)	33.17 (57.31)	68.04 (55.19)	104.63 (98.19)	174.67 (96.68)	120.83 (158.90)
	Range	1 - 290	0 - 337	0 - 275	6 - 342	49 - 347	24 - 470
Simple	*M (SD)*	56.66 (53.45)	37.96 (47.20)	65.08 (55.99)	105.34 (100.90)	63.27 (81.48)	127.36 (206.05)
	Range	0 - 250	0 - 210	1 - 275	1 - 383	0 - 326	0 - 948
Token Frequency							
Complex (all)	*M (SD)*	547.89 (886.64)	418.95 (809.25)	455.09 (618.58)	928.22 (1267.24)	1097.11 (1512.34)	1386.71 (2984.54)
	Range	1.10 - 6672.23	0 - 6500.52	0 - 2693.26	0.55 - 6419.04	0 - 5170.07	0 - 13523.64
+stem-suffix	*M (SD)*	335.28 (226.01)	465.45 (526.34)	266.67 (513.78)	895.22 (1514.49)	395.46 (876.23)	595.28 (1839.93)
	Range	126.47 - 817.74	44.17 - 1548.26	0 - 2693.26	0.55 - 6419.04	0 - 4365.51	0 - 13523.64
-stem+suffix	*M (SD)*	760.50 (1201.62)	372.44 (1020.14)	643.51 (660.44)	961.22 (972.71)	1798.76 (1687.17)	2178.13 (3649.84)
	Range	1.10 - 6672.23	0 - 6500.52	0 - 2457.89	3.84 - 4482.91	185.17 - 5170.07	136.61 - 10199.96
Simple	*M (SD)*	594.96 (780.90)	435.61 (785.40)	589.32 (636.28)	1009.41 (1315.30)	740.83 (1248.99)	1456.89 (3087.61)
	Range	0 - 3305.26	0 - 4118.88	0.55 - 2457.89	0.55 - 5985.07	0 - 5542.04	0 - 13523.64

Supplementary Table S2

Descriptives on trigram type and token frequencies for morphologically complex (+stem-suffix and -stem+suffix) and morphologically simple (-stem-suffix) pseudoword stimuli. It should be noted that differences are particularly observed on the fifth trigram position when a real suffix is present. Frequencies were extracted based on all the seven-letter words included in the E-Hitz database (Perea et al., 2006).

		Trigram Position				
		1	2	3	4	5
Type Frequency						
Complex (all)	*M (SD)*	9.02 (8.55)	4.14 (7.75)	5.96 (10.19)	10.57 (11.65)	27.43 (45.39)
	Range	0 - 31	0 - 41	0 – 63	0 - 43	0 – 157
+stem-suffix	*M (SD)*	15.43 (5.80)	4.65 (8.55)	4.07 (10.02)	4.26 (6.88)	3.52 (8.46)
	Range	4 - 22	0 - 39	0 – 63	0 - 30	0 – 40
-stem+suffix	*M (SD)*	2.61 (5.49)	3.63 (6.91)	7.85 (10.11)	16.89 (12.06)	51.33 (54.06)
	Range	0 - 31	0 - 41	0 – 43	3 - 43	4 – 157
Simple	*M (SD)*	3.39 (5.70)	4.57 (6.24)	6.61 (10.07)	8.5 (16.47)	9.35 (28.45)
	Range	0 - 40	0 - 25	0 – 57	0 - 119	0 – 220
Token Frequency						
Complex (all)	*M (SD)*	57.96 (77.28)	38.51 (111.56)	64.28 (243.06)	95.71 (185.64)	566.37 (1363.80)
	Range	0 - 313	0 - 743.13	0 - 2121.29	0 - 1071.76	0 - 4890.53
+stem-suffix	*M (SD)*	96.02 (73.73)	36.79 (115.15)	41.38 (170.29)	22.08 (48.90)	35.46 (102.78)
	Range	7.68 - 223.84	0 - 743.13	0 - 1149.67	0 - 218.63	0 - 607.34
-stem+suffix	*M (SD)*	19.90 (60.57)	40.22 (108.90)	87.18 (298.68)	169.34 (236.94)	1097.27 (1780.47)
	Range	0 - 313	0 - 620.23	0 - 2121.29	1.65 - 1071.76	5.76 - 4890.53
Simple	*M (SD)*	26.04 (134.51)	60.86 (228.52)	64.26 (218.65)	74.68 (191.16)	81.02 (333.09)
	Range	0 - 1378.17	0 - 1595.98	0 - 2121.29	0 - 1541.67	0 - 2866.91

Supplementary Table S3

Results from the generalized linear mixed model analysis for binomial outcomes for all the stimuli including initial and final trigram position type (a) and token (b) frequencies (total of 3599 datapoints-one subject was missing one response, 144 pseudowords and 25 participants).

a)

		Random Effects				
Group	Name	Variance	*SD*	Correlation		
Item	Intercept	0.04	0.19			
Subject	Intercept	0.80	0.89			
	Morph Complexity (complex)	0.04	0.19	-0.74		
	Fourth Position	1.90	1.38	-0.65	0.33	
	Seventh Position	1.39	1.18	-0.54	0.42	0.81

	Fixed Effects		
	β	*SE*	*p*
Intercept	1.66	0.22	<0.001
Initial position trigram type frequency	-0.06	0.04	0.10
Final position trigram type frequency	0.03	0.02	0.13
Fourth Position	-0.45	0.32	0.17
Seventh Position	-1.02	0.29	<0.001
Morph Complexity (complex)	0.07	0.18	0.70
Fourth Position:Morph Complexity (complex)	0.01	0.23	0.95
Seventh Position:Morph Complexity (complex)	0.10	0.22	0.64

b)

		Random Effects				
Group	Name	Variance	*SD*	Correlation		
Item	Intercept	0.03	0.18			
Subject	Intercept	0.80	0.89			
	Morph Complexity (complex)	0.04	0.19	-0.74		
	Fourth Position	1.91	1.38	-0.65	0.33	
	Seventh Position	1.39	1.18	-0.54	0.42	0.81

	Fixed Effects		
	β	*SE*	*p*
Intercept	1.68	0.22	<0.001
Initial position trigram token frequency	-0.03	0.02	0.10
Final position trigram token frequency	0.03	0.01	0.04
Fourth Position	-0.48	0.32	0.14
Seventh Position	-1.03	0.29	<0.001
Morph Complexity (complex)	0.05	0.18	0.79
Fourth Position:Morph Complexity (complex)	0.06	0.23	0.80
Seventh Position:Morph Complexity (complex)	0.11	0.22	0.63

Supplementary Table S4

Results from the generalized linear mixed model analysis for binomial outcomes for the morphologically complex stimuli including initial and final trigram position type (a) and token (b) frequencies (total of 1799 datapoints-one subject was missing one response, 72 pseudowords and 25 participants).

a)

		Random Effects				
Group	Name	Variance	*SD*	Correlation		
Item	Intercept	0.004	0.07			
Subject	Intercept	0.27	0.52			
	Morphological Structure (-stem+suffix)	0.01	0.12	0.61		
	Fourth Position	1.45	1.20	-0.4	-0.9	
	Seventh Position	0.94	0.97	-0.25	-0.88	0.73

	Fixed Effects		
	β	*SE*	*p*
Intercept	1.87	0.22	<0.001
Initial position trigram type frequency	-0.13	0.06	0.04
Final position trigram type frequency	0.02	0.02	0.44
Fourth Position	-0.65	0.33	0.05
Seventh Position	-0.81	0.29	0.005
Morph Structure (-stem+suffix)	-0.35	0.26	0.18
Fourth Position:Morph Structure (-stem+suffix)	0.66	0.31	0.03
Seventh Position:Morph Structure (-stem+suffix)	-0.08	0.29	0.79

b)

		Random Effects				
Group	Name	Variance	*SD*	Correlation		
Subject	Intercept	0.27	0.52			
	Morphological Structure (-stem+suffix)	0.01	0.12	0.61		
	Fourth Position	1.45	1.20	-0.4	-0.9	
	Seventh Position	0.95	0.97	-0.25	-0.88	0.73

	Fixed Effects		
	β	*SE*	*p*
Intercept	1.85	0.21	<0.001
Initial position trigram token frequency	-0.05	0.03	0.10
Final position trigram token frequency	0.05	0.02	0.03
Fourth Position	-0.58	0.33	0.08
Seventh Position	-0.84	0.29	0.003
Morph Structure (-stem+suffix)	-0.41	0.26	0.12
Fourth Position:Morph Structure (-stem+suffix)	0.59	0.31	0.06
Seventh Position:Morph Structure (-stem+suffix)	-0.05	0.29	0.86