The hyphen as a segmentation cue in triconstituent compound processing: It's getting better all the time

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Inserting a hyphen in Dutch and Finnish compounds is most often illegal given spelling conventions. However, the current two eye movement experiments on triconstituent Dutch compounds like *voetbalbond* ''footballassociation'' (Experiment 1) and triconstituent Finnish compounds like *lentokenttätaksi* ''airporttaxi'' (Experiment 2) show that inserting a hyphen at constituent boundaries does not have to be detrimental to compound processing. In fact, when hyphens were inserted at the major constituent boundary (*voetbal-bond* ''football-association''; *lentokenttä-taksi* ''airport-taxi''), processing of the first part (*voetbal* ''football''; *lentokenttä* ''airport'') turns out to be faster when it is followed by a hyphen than when it is legally concatenated. Inserting a hyphen caused a delay in later eye movement measures, which is probably due to the illegality of inserting hyphens in normally concatenated compounds. However, in both Dutch and Finnish we found a learning effect in the course of the experiment, such that by the end of the experiments hyphenated compounds are read faster than in the beginning of the experiment. By the end of the experiment, compounds with a hyphen at the major constituent boundary were actually processed equally fast as (Dutch) or even faster than (Finnish) their concatenated counterparts. In contrast, hyphenation at the minor constituent boundary (*voet-balbond* ''foot-ballassociation''; *lento-kenttätaksi* ''air-porttaxi'') was detrimental to compound processing speed throughout the experiment. The results imply that the hyphen may be an efficient segmentation cue and that spelling illegalities can be overcome easily, as long as they make sense.

Key words: Eye movements, compounds, learning, branching, segmentation.

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INTRODUCTION

In spoken word recognition it is not always easy to decide where one word ends and where the other begins. Typically there are no pauses in the acoustic waveform at word boundaries and listeners have to use segmentation cues like stress patterns or phoneme co-occurrence information to demarcate word boundaries (e.g., Cunillera, Toro, Sebastián- Gallés & Rodríguez-Fornells, 2006; Vroomen, Tuomainen & De Gelder, 1998). Whereas these segmentation cues in spoken word recognition are rather subtle, in most written languages word boundaries are marked more saliently, most notably by the interword space. The interword space makes the task of locating word boundaries, and with that the task of reading in general, seemingly easy. Therefore it may come as no surprise that in spaced languages reading slows down to a great extent (by 30–50%, see e.g., Malt & Seamon, 1978; Morris, Rayner & Pollatsek, 1990; Perea & Acha, 2009; Rayner, Fischer & Pollatsek, 1998; Winskel, Radach & Luksaneeyanawin, 2009) if interword spaces are removed or filled with extraneous letters.

However, interword spacing does not solve all the possible word segmentation problems. More specifically, most languages allow existing words to be combined to form multi-word formations called compound words. The words inside compound words are often called lexemes or constituents and the number of constituents within a compound can vary from two (e.g., tooth/paste[1]) to many (e.g., four constituents as in the Finnish liikenne/turvallisuus/asian/tuntija ''expert in traffic safety''). Hence compound words are quite often of considerable length. Typically, long compound words cannot be dealt with in one single fixation and readers make use of constituent information to process them (Bertram & Hyönä, 2003; Kuperman, Bertram & Baayen, 2008). Thus, it is beneficial to locate the constituent boundary and with that the constituents as quickly as possible. In other words, also in reading spaced languages there is an additional need for appropriate segmentation cues that set one constituent apart from the other. The current study investigates the effect of such a segmentation cue in Finnish and Dutch, two languages with productive compounding and a large number of long compounds. More specifically, it investigates the role of the hyphen in processing triconstituent Dutch and Finnish compounds.

Earlier studies showed that readers are indeed sensitive to segmentation cues in compound processing (Bertram, Pollatsek & Hyönä, 2004; Inhoff, Radach & Heller, 2000; Juhasz, Inhoff & Rayner, 2005). For example, readers may make use of specific letter co-occurrence information to identify constituent boundaries. In Finnish, for instance, there are vowel harmony regulations, which prescribe that – with the exception of compound words – front vowels (ä, ö, y) and back vowels (a, o, u) never appear in one and the same word. Consequently, identifying front and back vowels in the same word provides an explicit cue that the word in question is a compound word. Moreover, when these different types of vowels are at the constituent boundary (as in *jäätelö/auto* ''ice cream truck'') or around the constituent boundary (as in *myymylä/varas* ''shop lifter''), segmentation of the compound becomes much easier, yielding faster reading times for these kinds of compounds than for compounds with the same

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types of vowels throughout (e.g., *inflaatio/uhka* ''inflation threat'' or *kirkkojuhla* ''church celebration''; see Bertram *et al*., 2004).

English offers another solution by making use of spaces within compound words to demarcate constituent boundaries (e.g., *dwelling association*). However, the problem with the interconstituent space is that meaning integration of the individual constituents becomes much harder, especially in context (Staub, Rayner, Pollatsek, Hyönä & Majewski, 2007). That is, even though in spaced compounds it is easier to locate constituent boundaries and identify individual constituents, it is much more troublesome to realize that constituents belong to one and the same lexical unit. Consequently, it is much harder to compose or retrieve the meaning of spaced compounds than to compose or retrieve the meaning of concatenated compounds. Both the results of Inhoff *et al.* (2000) and Juhasz *et al.* (2005) are in line with this view. In both eye movement studies there was an initial processing advantage for spaced compounds in comparison to concatenated compounds – as reflected in an early measure on the word (first fixation duration). However, spaced compounds were disadvantaged in later stages of processing as reflected in more global or later measures such as gaze duration (the summed duration of all fixations on the target word before fixating away from it, Juhasz *et al*., 2005), last fixation duration on the target word or gaze duration on the next word (Inhoff *et al*., 2000).

As noted above, in the current study on triconstituent Dutch (Experiment 1) and Finnish compounds (Experiment 2) and in a parallel study on biconstituent Finnish compounds (Bertram & Hyönä, submitted), we considered the hyphen as a segmentation cue. Our hypothesis was that the hyphen is a very good segmentation cue, since it is visually salient and hence clearly indicates where the constituent boundary is. However, unlike spaces, it also indicates that constituents belong together, that is, it clearly indicates that the constituent(s) following the hyphen belongs to one and the same word as the constituent(s) preceding the hyphen. Therefore we hypothesized that processing costs inflicted on compound processing by an interconstituent space should be reduced or eliminated in hyphenated compounds. In the Bertram and Hyönä study (submitted) we found that for long biconstituent Finnish compounds this is indeed the case. More precisely, in this study the first constituent (e.g., *vaihto* ''exchange'') of a legally hyphenated biconstituent compound (e.g., *vaihto-ohjelma*[2] ''exchange program'' was processed much faster than the first constituent (*potilas* ''patient'') of a concatenated compound (*potilashuone* ''patient (waiting) room''). However, later measures did not indicate that the hyphen inflicts a processing cost on compound processing: gaze durations for the whole compound were shorter for *vaihto-ohjelma* than for *potilashuone*. In fact, the processing advantage for hyphenated compounds acquired in the early stages (as reflected in the gaze duration on the first constituent) was the same as the processing advantage for reading the whole compound.

On the basis of these results, one may indeed conclude that the hyphen is a more beneficial cue than the space in compound processing. However, it should be noted that the earlier studies on spaced compounds are not completely comparable to the study of Bertram and Hyönä (submitted). For instance, the spaced German compounds used by Inhoff *et al.* (2000) (e.g., *Daten Schutz Experte* ''data safety expert'') do not accord with German spelling conventions, as there is no spacing or capitalization of later constituents in German compounds. It may well be that the illegality of spelling in these compounds caused the extra processing costs in later stages of processing (in comparison to the correctly spelled unspaced version of the word, *Datenschutzexperte*). This raises the question what would happen, if hyphens were illegally inserted in existing compounds. Would the illegality disturb compound processing to such an extent that processing benefits due to speeded-up segmentation would eventually be attenuated or eliminated? Or would the reader gratefully accept the hyphen and largely neglect the illegality?

To answer these kinds of questions, we inserted hyphens in Dutch and Finnish triconstituent compounds (e.g. Dutch: *voetbalbond* ''football-association''; Finnish: *lentokenttä- taksi* ''airport-taxi'') that normally are written in concatenated format. We expected that the hyphen would come to aid in segmentation and would consequently allow for faster identification of the constituents at the left side of the hyphen. That is, we expected that *voetbal* is more quickly recognized in *voetbal-bond* than in *voetbalbond*. In addition, we also expected a later processing cost given the fact that the insertion of hyphens is not in accord with Dutch and Finnish spelling conventions.[3] However, since the hyphen – unlike the space – indicates that the three constituents belong together, the illegality of spelling could be overcome quite easily and compound processing might proceed equally smoothly if not faster when presented in hyphenated format than when presented in concatenated format. We will assess the time course of triconstituent compound processing by more detailed analyses for separate constituents and two-constituent clusters of the Dutch and Finnish compounds.

Naturally, triconstituent compounds are more complex than biconstituent compounds.[4] Most importantly, for the latter type of compounds in head-final languages like Finnish, Dutch, English or German the rightmost constituent determines the syntactic category and the basic meaning of the compound. In these compounds, it is clear then that the first constituent modifies the second. However, for the triconstituent compounds a reader has to figure out whether the first constituent modifies the second and third constituent as in *zaalvoetbal* ''indoor football'' or whether the first two constituents together modify the third as in *voetbalbond* ''football association''. Compound words like *zaalvoetbal* are called right-branching, since the right part of the compound can be further branched into *voet* and *bal* and compound words like *voetbalbond* are called left-branching, since the left part of the compound can be further branched into *voet* and *bal*. Consequently, words like *zaalvoetbal* have a major constituent boundary between *zaal* and *voetbal* and a minor constituent boundary between *voet* and *bal*, whereas *voetbalbond* has a major constituent boundary between *voetbal* and *bond* and a minor constituent boundary between *voet* and *bal*. Intuitively, inserting a hyphen at the major constituent boundary (*voetbal-bond* ''football-association''; *zaal-voetbal* ''indoor-football'') seems more natural than inserting a hyphen at the minor constituent boundary (*voet-balbond* ''foot- ballassociation''; *zaalvoet-bal* ''indoorfoot-ball'').

This is supported by studies of Libben (1993, 1994), who conducted naming experiments on trimorphemic left-branching and right-branching English derivations with nonsense roots (e.g., left-branching: *rebirmable*; right-branching: *rebirmize*). A nonsense derivation like *rebirmable* is left-branching, since the prefix *re-* only attaches to verbs and whereas *birm* is a potential verb, *birmable* is not. Hence *rebirm* needs to be formed before *rebirmable*, yielding a left-branching structure. Adversely, the suffix *–ize* attaches to nouns but not to verbs and since *birm* but not *rebirm* can be a noun, *birmize* needs to be formed before *rebirmize*, yielding a right-branching structure. In order to ensure that *re-* would be recognized as a prefix, Libben inserted a hyphen between the prefix and the root (e.g., *re-birmable*, *re-birmize*). However, by so doing, Libben supported the right-branching structure (*rebirmize*) to a greater extent than the left-branching structure (*rebirmable*) and hence it may come as no surprise that in his studies right-branching nonce derivations were responded to equally fast (Libben, 1993) or faster (Libben, 1994) than left-branching ones, which goes against the left-to-right processing hypothesis (Hudson & Buijs, 1995) and against some more recent studies showing a processing advantage for left-branching structures (e.g., Pollatsek, Drieghe, Stockall & de Almeida, 2010; Yin, Derwing & Libben, 2004). Also the fact that in English spaces are more often inserted at the major constituent boundary (cf. *football association*) and interfixes in Dutch and German are more often present at major constituent boundaries (e.g., *grondwetsartikel* ''ground law article'' = ''constitution article'', with the interfix *-s-* at the major constituent boundary, see Krott, Libben, Jarema, Dressler, Schreuder & Baayen, 2004) supports the notion that a clear visual cue may facilitate the resolution of the hierarchical morphological structure of triconstituent compounds.

For the current experiments we selected triconstituent Dutch (Experiment 1) and triconstituent Finnish (Experiment 2) compounds, which we presented either in concatenated format, with the inclusion of a hyphen at the major constituent boundary, or with the inclusion of a hyphen at the minor constituent boundary. As previous studies investigating segmentation cues in compound processing, this study was also an eye movement study with target compound words presented in declarative sentences, allowing us to follow the time course with which inserted hyphens exerted an effect on compound processing.

Following the argumentation outlined above, our prediction was that hyphenation at the major constituent boundary would yield the segmentation process more successful than in case of concatenated compounds, reflected in faster processing times in early eye movement measures (in line with Bertram & Hyönä, submitted; Inhoff *et al*., 2000; Juhasz *et al*., 2005). However, we also expected a later processing cost, given the fact that the inserted hyphens did not follow Dutch and Finnish spelling conventions. At any rate, we expected these costs to be less than in previous studies with inserted spaces, since – even though illegal – an inserted hyphen, unlike an inserted space, indicates that the three constituents in a triconstituent compound belong to one and the same word. With respect to hyphenation at the minor constituent boundary, we thought it may not be completely detrimental to offer a hyphen here, since also words like *voetbal* ''football, soccer in Am. English'') may be decomposed and recognized – at least to some extent – via their constituents and giving additional information as to where the minor constituent boundary is may facilitate the decomposition process. If this is the case, we would not expect to see much of a difference in early processing measures for compounds with hyphenation at a minor boundary in comparison to concatenated compounds. However, it is likely that later processes of meaning integration will be disturbed. That is, even though the initial identification of *voet* and perhaps *bal* in *voet-balbond* may run smoothly, the hyphen here does indicate that the meaning of *bal* should be integrated with *bond* and that *voet* modifies the integrated meaning of these constituents, which is – naturally – not the case.

Morphology and learning

One aspect that is not often considered in studies on language processing is that participants might learn during an experiment. In this study we investigated whether triconstituent compounds are processed more efficiently in the end of the experiment than in the beginning. Naturally, we were mostly interested in whether a possible improvement in the course of the experiment depended on presentation style of the compounds (concatenated vs. major boundary hyphenation vs. minor boundary hyphenation). We expected that a hyphenated compound would benefit more from repeated exposure to other hyphenated compounds than concatenated compounds would benefit from repeated exposure to other concatenated compounds. This is because we thought that participants would have to get used to the illegally spelled compounds, before coming up with an optimal way to process these compounds. Generally, one may expect that triconstituent compounds are so complex that repeated exposure within a short time-frame may generate training effects across all presentation styles, but we expected additional benefits for hyphenated ones related to adaptation to the illegality of spelling. In addition, we hypothesized that for Finnish adaptation to the illegally hyphenated compound words may be faster, since hyphenation in general is more common for Finnish compound words than Dutch ones. That is, in both Finnish and Dutch compounds hyphenation is prescribed when the first constituent ends with the same vowel as the second one begins with (Dutch: *zee-eend* ''sea duck''; Finnish: *vaihto-ohjelma* ''exchange program''), but in Finnish there are more compound words where this is the case by virtue of more productive compounding in general (see Moscoso del Prado Martín, Bertram, Häikiö, Schreuder & Baayen, 2004) and more words ending in a vowel. In order to assess whether progress in the experiment came with relatively more improvement for hyphenated compounds than for concatenated compounds, we considered whether the position of trial N in the experimental list interacted with compound presentation style. We did this for both Dutch and Finnish in order to assess whether specific language characteristics would affect the learning curves in each language.

EXPERIMENT 1

In Experiment 1, we tested the effect of hyphenation on the processing of triconstituent Dutch compounds in sentential context. Both left-branching (*voetbalbond* ''football association'') and right-branching (*zaalvoetbal* ''indoor football'') were included in the experiment. The main goal was to test how concatenated Dutch compounds (*voetbalbond*, *zaalvoetbal*) are processed in comparison to compounds hyphenated at major constituent boundaries (*voetbal-bond*, *zaal-voetbal*) and minor constituent boundaries (*voet-balbond*, *zaalvoet-bal*). In addition, it was investigated whether the effect of hyphenation changes in the course of the experiment.

Method

Participants. Twenty-four students of the Radboud University Nijmegen (18 females and 6 males) were paid €6 to participate in this experiment. All were native speakers of Dutch and had normal or corrected-to-normal vision.

Apparatus. Eye movements were recorded with an EyeLink II eyetracker manufactured by SR Research Ltd. (Canada). The eyetracker is an infrared video-based tracking system combined with hyperacuity image processing. The eye movement cameras are mounted on a headband (one camera for each eye), but the recording was monocular (right eye) and in the pupil-only mode. There are also two infrared LEDs for illuminating the eye. The headband weighs 450 g in total. The cameras sample pupil location and pupil size at the rate of 500 Hz. Recording is performed by placing the camera and the two infrared light sources 4–6 cm away from the eye. Head position with respect to the computer screen is tracked with the help of a head-tracking camera mounted on the center of the headband at the level of the forehead. Four LEDs are attached to the corners of the computer screen, which are viewed by the head-tracking camera, once the participant sits directly facing the screen. Possible head motion is detected as movements of the four LEDs and is compensated for on-line from the eye position records. The average gaze position error of EyeLink II is <0.5°, while its resolution is 0.01°. These values are taken from the manufacturer. Also, the fixation detection algorithm is provided by the manufacturer. The stimuli were presented on a 17-inch computer screen, which had a refresh rate of 60 Hz.

Materials. The set of target words comprised 138 Dutch triconstituent compounds. Of these, 95 were left-branching (e.g., *voetbalbond* ‘‘football association’’) and 43 were right-branching (e.g., *zaalvoetbal* ‘‘indoor football’’). The main factor of interest was compound presentation style, *CmpPresStyle*. There were three different presentation styles: correctly spelled concatenated compounds without hyphenation (the *None*-condition: *voetbalbond*, *zaalvoetbal*), illegally spelled compounds presented with hyphens at the major constituent boundary (the *Major*-condition: *voetbal-bond*, *zaal-voetbal)* and illegally spelled compounds presented with hyphens at the minor constituent boundary (the *Minor*-condition: *voet-balbond, zaalvoet-bal*). For the left-branching compounds, we chose words that included an incorporated compound at the left side (e.g., *voetbal* in *voetbalbond*) with an average frequency of about 5 per million, but with a non-existing or very low- frequency compound at the right side (*balbond* ‘‘ball association’’) with an average frequency of 0.03 per million (all frequencies for Dutch are obtained from the CELEX lexical database with 42 million tokens, Baayen, Piepenbrock & Gulikers, 1995). For the right-branching compounds, we chose words that included an incorporated compound at the right side (*voetbal* in *zaalvoetbal*) with an average frequency of about 16.85 per million, but with a non-existing or very low-frequent compound (*zaalvoet* ‘‘indoor foot’’) at the left side (average frequency 0.13 per million). It should be noted that the unequal distribution of left-branching and right-branching compounds in our experiment follows the distribution in the Dutch language at large, where left-branching compounds are also far more common than right-branching ones. Lexical statistical properties of the target compounds can be found in Table 1.

Each target word was embedded in a separate sentence, and the target word never occupied the sentence-initial or sentence-final position. The sentences were no longer than one line of text (82 characters) and had a neutral sentence beginning. An example sentence would be: *De Nederlandse voetbalbond/voetbal-bond/voet-balbond heeft een speciale trainerscursus voor profvoetballers opgestart* ‘‘The Dutch footballassociation/football-association/foot-ballassociation has started a special trainer’s course for professional football players’’. Three lists of stimuli were prepared so that a given compound word appeared as *None* in the first list, as *Major* in the second list and as *Minor* in the third list. Thus each list contained 46 concatenated compounds, 46 compounds with hyphenation at the major constituent boundary and 46 compounds with hyphenation at the minor constituent. The presentation of the stimulus lists was counterbalanced across participants, such that each participant saw any given compound in only one condition.

The sentences were displayed one at a time starting at the central-left position on the computer screen. Stimuli were presented in fixed-width font (Courier New, size 12). With a viewing distance of about 80 cm, one character space subtended approximately 0.36° of visual angle. In addition to the 138 target sentences, there were 156 filler sentences. Sentences were presented in two blocks: the order of sentences within the blocks was pseudo-randomized and the order of blocks was counterbalanced across participants. Approximately 15% of sentences were followed by a yes-no question pertaining to the content of the sentence. The experiment began with a practice session consisting of five filler sentences and two questions.

Procedure. Prior to the presentation of the stimuli, the eye-tracker was calibrated using a three-point grid that extended over the horizontal axis in the middle of the computer screen. Prior to each stimulus, correction of calibration was performed by displaying a fixation point in the central-left position. After calibration, a sentence was presented to the right

Table 1. *Lexical-statistical properties (ranges in parentheses) of the Dutch triconstituent compounds with properties of left-branching and right-branching compounds separately (Experiment 1)*

	Compound type		
	All	Left-branching	Right-branching
N	138	95	43
Example	–	*voetbalbond*	*zaalvoetbal*
Whole word frequency[a]	0.24 (0.05–2.5)	0.22 (0.05–1.7)	0.28 (0.05–2.5)
1st constituent frequency[a]	5.7 (0.001–46)	6.5 (0.001–46)	4.0 (0.031–23)
2nd constituent frequency[a]	7.0 (0.003–46)	4.2 (0.003–27)	13.2 (0.012–46)
3rd constituent frequency[a]	2.9 (0.003–41)	3.9 (0.019–41)	0.7 (0.003–5)
Frequency 1st and 2nd constituent together[a]	3.4 (0–39)	4.9 (0–39)	0.03 (0–0.6)
Frequency 2nd and 3rd constituent together[a]	5.34 (0–135)	0.13 (0–5.8)	16.85 (0.1–135)
Word length[b]	14.5 (10–21)	14.7 (10–21)	14.2 (10–18)
1st constituent length[b]	4.7 (2–9)	4.4 (2–7)	5.4 (3–9)
2nd constituent length[b]	4.5 (3–8)	4.5 (3–8)	4.3 (3–7)
3rd constituent length[b]	5.4 (3–10)	5.7 (3–10)	4.5 (3–7)

[a] per million; [b] in characters.

of the fixation point. Participants were instructed to read sentences silently for comprehension at their own pace and to press a ''response'' button on the button box when they were done. Upon presentation of a question, participants pressed either the ''yes'' button or the ''no'' button on the button box. If no response was registered after 3000 ms, the stimulus was removed from the screen and the next trial was initiated. Responses and response times of participants were recorded along with their eye movements. The experimental session lasted for 50 minutes at most.

Dependent variables. We used a number of eye-movement measures as indices of compound processing. A common measure to assess global processing time is gaze duration on a word. As noted earlier, gaze duration is the summed duration of all fixations on the target word before fixating away from it. Next to this measure we considered two measures that may be indicative of later processing stages, namely selective regression path duration (the summed duration of all fixations on the target word before fixating to the right of that word) and total fixation time (the summed duration of all fixations on the compound). Before presenting the results in full, we note that the results in these two measures were similar to the gaze duration results and will only be discussed briefly. Finally, we broke down gaze duration into subgaze duration measures in order to assess the time course by which morphological information becomes available. Since these subgazes are directly linked to constituent (integration) processing, we considered them to be more insightful than first fixation duration. We will come back to these subgaze measures in more detail below. The measures used to assess triconstituent compound processing are visualized in Fig. 1.

Predictors. Apart from the critical manipulation coded as *CmpPresStyle*, we also considered a number of variables that have been established in earlier research as reliable predictors of compound processing. Thus, we took into consideration compound length in characters (*WordLength*), and its frequency of occurrence (*WordFreq*). We also collected information on the frequencies, lengths and sizes of morphological families of the first (*voet*), second (*bal*) and third constituents (*bond*), separately. These were coded as *LengthFirst*, *FreqFirst*, *FamFirst*, and so on. Where applicable, we also coded frequencies and family sizes of the combinations of the first two (*voetbal*) and last two (*balbond*) constituents. To account for potential learning effects we also included stimulus position in the experimental list (*TrialNum*). We standardized the values of *TrialNum* by subtracting the mean and dividing it by one standard deviation, to make the range of this predictor comparable to those of other predictors. Since the literature on triconstituent compounds points to the predictive role of branching in compound recognition, we coded our target compounds for branching (binary variable *Branching,* with levels *LeftBranching* or *RightBranching*). Also, to control for the possible influence of previous words in the sentence on the processing of our targets, we included the total number of words in sentence (*TotalWords*) and the ordinal word position in sentence (*NumWord*) as predictors (see Kuperman, Dambacher, Nuthmann & Kliegl, 2010, for the relevance of this factor on word processing speed).

SubgazeC1C2: Fixation 4+5
SubgazeC3: Fixation 6
Gaze duration: Fixation 4–6
Selective regression path duration: Fixation 4–6+8
Total fixation duration: Fixation 4–6+8+10

Fig. 1. Hypothetical eye fixation pattern on the sentences phrase *De Nederlandse voetbalbond heeft …* ''The Dutch football association has ...'' including the triconstituent left-branching target word *voetbalbond*. Eye movement measures used in our analyses are listed in the legend.

Statistical considerations. We log-transformed all fixation duration and frequency measures to reduce the skewness of respective distributions and attenuate the influence of outliers on the predictions of statistical models. The distribution of duration measures was skewed even after the log-transformation. Likewise, residuals of the multiple regression models for durations were almost always skewed. To reduce skewness, we removed outliers from the respective datasets, that is, points that fell outside the range of −2.5 to 2.5 units of SD of the residual error of the model. Once outliers were removed (ranging from 1 to 3% of data points between models), the models were refitted to the trimmed datasets.

We made use of multiple regression mixed-effects modeling with, among others, participants and items as crossed random effects, allowing us to explore simultaneously many predictors, both factors and covariates, while accounting for between-participants and between-items variance (cf. Baayen, Davidson & Bates, 2008; Bates & Sarkar, 2005). Word ID (*Word*) and participant ID (*Subject*) were included in each statistical model as random effects, as were other random slopes and contrasts (see Appendix 1 for the random effect structure and see Baayen *et al*., 2008, for an explanation how to achieve the optimal random effect structure). Below and in Appendix 1 we only report the parsimonious models with the effects and interactions that retained statistical significance below the 0.05 threshold in the stepwise backward elimination procedure using the model comparison likelihood ratio test. Similarly, we only report non-linear effects of our covariates, where their increased performance, as compared to linear effects, is supported by the model comparison tests. We only considered interactions that were critical for the questions of interest (e.g. the interaction of the compound presentation format by the ordinal number of trial, as a proxy of the learning effect) or were suggested as influential by earlier research (e.g. the interaction of compound frequency by the compound's constituent family size or its frequency in Kuperman *et al*., 2008, 2009). All random effects significantly improved the performance of respective models, as indicated by the model comparison using the likelihood ratio test. Thus, while initially the sets of predictors were almost identical between Dutch and Finnish models, the final models (see Appendix 1) differ in the constellation of random and fixed effects.

Specifications for the models reported in Appendix 1 present the output of the pvals.fnc() function in library languageR of R statistical software (R Development Core Team, 2007). The specifications include estimates of the regression coefficients; highest posterior density intervals (HPDs), which are a Bayesian measure of confidence intervals; *p*-values estimated by the Monte Carlo Markov chain (MCMC) method using 5,000 samples; and *p*-values obtained with the *t*-test for fixed effects using the difference between the number of observations and the number of fixed effects as the upper bound for the degrees of freedom (for the detailed treatment of the method, see Baayen, 2008; Baayen *et al*., 2008; Pinheiro & Bates, 2000). For the effects reported in the body of the paper we provide *p*-values estimated by the MCMC method using 5,000 samples.

Results

We excluded fixations with durations below 50 ms and above 1,000 ms, as well as pooled together fixations that bordered micro-saccades (i.e., successive saccades landing within one character, 186 data points). Our inspection of eye-movement patterns in the reading of compound revealed a relatively large number of cases (about 20%) in which the first fixation on the target compound landed on its initial characters and was immediately followed by a regressive saccade. Given the lengths of our compounds, this pattern of eye movements is partly explainable by saccadic overshoot, that is, it is likely that the targeted word was the word preceding the compound (see Drieghe, Rayner & Pollatsek, 2008). Perhaps the immediate regressions are also partly related to a rolling-up-the-sleeves strategy. That is, readers may on some occasions after a quick inspection realize that a long, relatively low-frequent word is coming up and that they better take care that the previous context is fully understood in order to efficiently deal with this word (see Bicknell & Levy, 2010, for a similar hypothesis). At any rate, we felt it was safest to disregard these cases from our analyses as lacking insight into compound processing as such. The number of cases excluded was equal across conditions (all around 20%). Gaze duration, selective regression path duration and total fixation time showed the same pattern of results with respect to variables of our interest, and hence we chose to focus (below and in Appendix 1) on one of the measures, gaze duration, which is the most regularly used eye movement measure in reading research (although we will briefly report selective regression path duration and total fixation time results as well). Our final data set for the gaze duration measure comprised 5384 data points. With respect to the number of fixations in first-pass reading, 13% of compounds elicited a single fixation, 36% elicited two fixations, 25% elicited three fixations and 26% elicited four or more fixations.

The critical manipulation of the experiment was that of compound presentation style. The difference between conditions *None* (compound presented in a concatenated form) and *Major* (compound with hyphenation at the major constituent boundary) failed to reach significance in the early (gaze duration, 547 ms and 578 ms, respectively) and later (selective regression path duration, and total fixation time) eye-movement measures, *p*s > 0.05. However, gaze duration for both the *None*-condition and the *Major*-condition was significantly shorter than the gaze duration for the *Minor*-condition (646 ms), *p*s < 0.001.

As morphological learning is a topic of our interest, we considered the interaction of compound presentation style (*CmpPresStyle*) with the compound position in the experimental list (*TrialNum*). This interaction importantly qualifies the effects reported above and reflects differential learning effects for conditions of compound presentation. Figure 2 Panel D plots the effect of *TrialNum* on gaze duration broken down by presentation style (see Appendix 1 for the full model for gaze duration). As can be seen in this figure, gaze durations are substantially shorter towards the end of the experiment in conditions *Major* and *Minor*, but not in condition *None*. Moreover, the effect of *TrialNum* for *Major* and *Minor* is not significantly different from each other. Also, by the end of the experiment processing times for compounds with a hyphen at the major constituent boundary are on par with processing times for concatenated compounds. This set of findings indicates that readers adapt to the exposure to illegal spelling and are able to attenuate its impact on the processing speed.

For illustrative purposes, we split up the experiment in two halves and assess how the *Major* and *Minor* conditions compare to the *None* condition at either side of the experimental lists (This procedure is statistically suboptimal (see Cohen, 1983), but may be more familiar to readers that are not used to regression designs). In the first half of the experiment (up to position 180 in

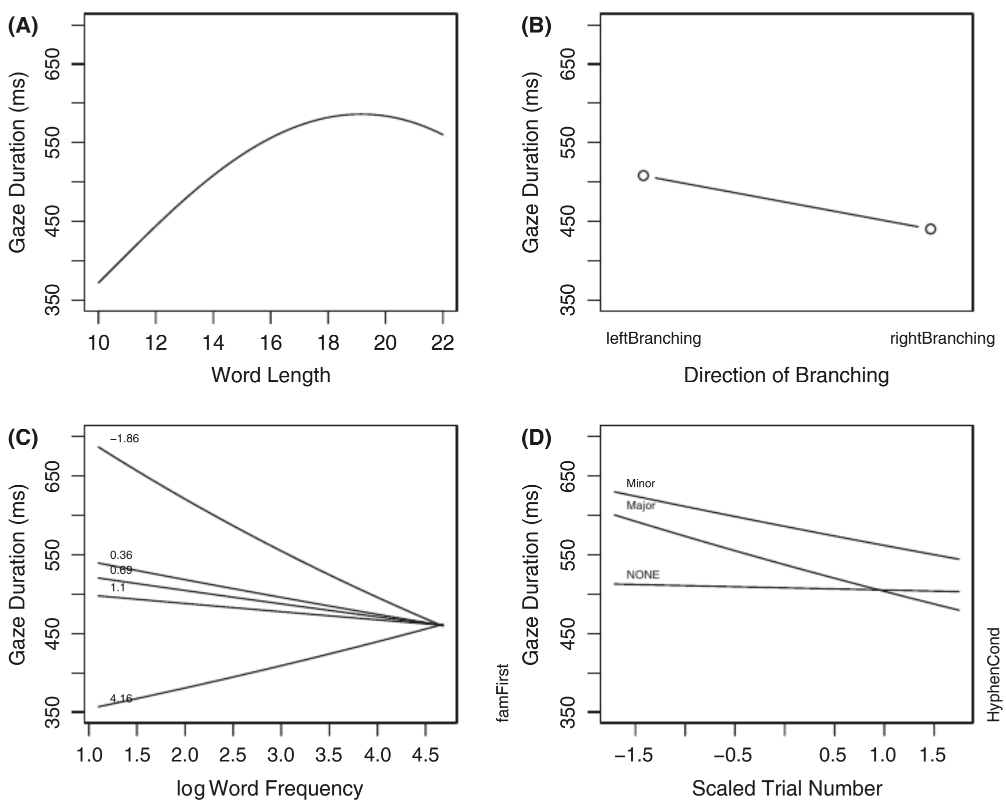

Fig. 2. Partial effects on gaze duration in Experiment 1 of (A) Word Length. (B) Direction of Branching. (C) The interaction of compound frequency by first constituent family size: The effect of compound frequency is plotted for quartiles of first constituent family size (values shown at the left margin). Compound frequency has a strongest negative effect when family size is the smallest; the effect decreases as the family size increases, and becomes weakly positive for compounds with the largest first constituent family size. (D) The interaction of standardized trial number by compound presentation style. There is a learning effect in conditions *Major* and *Minor*, but not in condition *None*.

the experimental list) gaze durations for compounds with hyphens at the major constituent boundary are significantly longer (mean = 608, SD = 288) than gaze durations for concatenated compounds (mean = 547, SD = 297), as supported by the two-tailed *t*-test ($t(903) = -4.39$, $p < 0.001$). Yet, crucially, in the second half of the experiment (from position 180 onwards) gaze durations in conditions *Major* and *None* (mean = 559, SD = 319 vs. mean = 550, SD = 265) do not differ significantly from each other ($t < 1$). While compounds in the *Minor* presentation condition show a reduction in reading times from the first half (mean = 662, SD = 333) to the second half (mean = 636, SD = 297) of the experiment, in both halves the gaze durations were significantly longer than in the other two conditions (all *p*s < 0.05 after Bonferroni correction).

Detailed analyses of the hyphenation effect. In order to assess the advantage that compounds in conditions *Major* and *None* demonstrate over compounds in condition *Minor*, we opted for considering finer-grained eye-movement measures to pin down the processing stages when these advantages accrue. To this end, we considered left-branching and right-branching compounds separately, since major and minor constituent boundaries have different positions across the two types of branching. More precisely, for left-branching compounds (where the first two constituents modify the third as in *voetbalbond*, henceforth represented as C1C2-C3) we considered the following measures: SubgazeC1C2 (the first-pass reading time of the first two constituents before exiting this area, see Fig. 1), SubgazeC3 (the first-pass reading time of the third constituent before exiting this area, see Fig. 1), NrFixC1C2 (the number of fixations in first-pass reading on the first two constituents before exiting this area) and NrFixC3 (the number of fixations in first-pass reading on the third constituent before exiting this area). For right-branching compounds (where the first constituent modifies the second and third as in *zaalvoetbal*, henceforth represented as C1-C2C3) we considered the following measures: SubgazeC1 (the first-pass reading time of the first constituent before exiting this area), SubgazeC2C3 (the first-pass reading time of the last two constituents before exiting this area), NrFixC1 (the number of fixations in first-pass reading on the first constituent before exiting this area), and NrFixC2C3 (the number of fixations in first-pass reading on the last two constituents before exiting this area). In both types of branching, we have excluded from consideration the cases when no fixations were made on the constituents in question (number of exclusions can be derived from skipping rates as reported below). Mean values of the resulting eye-movement measures for left-branching compounds are represented in Table 2. All effects reported below are observed in multilevel regression models with participants and words as random effects.

Table 2 indicates that left-branching compounds with hyphenation at the major constituent boundary elicit shortest reading times on the first two constituents (SubgazeC1C2) and the lowest number of fixations on these constituents (NrFixC1C2). The multilevel regression models (with the Poisson link function for the fixation count measures) reveal that the difference between *Major* and the other two conditions is highly significant for both measures (all *p*s < 0.01; models not shown), while the contrast between *Minor* and *None* is not significant (all *p*s > 0.1). Yet, the advantage of *Major* in the processing of the C1C2-constituent cluster is set off by slower recognition of C3 in comparison to concatenated compounds (condition *None*), which emerges in significantly longer subgaze durations ($t(1351) = 3.63$, $p < 0.001$) and a greater number of fixations on C3 ($p = 0.02$) for *Major* than for *None*. For compounds in the *Minor* condition, subgazeC3 is the slowest of all three conditions (all *p*s < 0.05) and the NrFixC3 for the *Minor* condition is significantly greater than for *None* ($p < 0.01$) and on par with *Major* ($p > 0.1$). As a result, the mean gaze duration for the left-branching compounds does not show a significant difference between concatenated compounds and those with hyphenation at the major constituent boundary ($t(1834) = 0.72$, $p > 0.1$), but both of these conditions elicit shorter gaze durations than compounds with a hyphen inserted at the minor constituent boundary (all *p*s < 0.001 after Bonferroni correction).

Table 2. *Eye fixation measures as a function of presentation style for left-branching Dutch compounds*

Eye fixation measure	Compound presentation style		
	Concatenated (*voetbalbond*)	Major boundary (*voetbal-bond*)	Minor boundary (*voet-balbond*)
Gaze duration	577	595	647
SubgazeC1C2	483	384	489
SubgazeC3	245	273	290
NrFixC1C2	1.84	1.51	1.82
NrFixC3	1.07	1.13	1.17

Table 3 reports mean values of the duration measures and fixation counts for the right-branching compounds. Right-branching compounds in condition *Major* demonstrate shorter subgaze durations for constituent C1 in comparison to the other two conditions (all *p*s < 0.01 after Bonferroni correction). Yet – as with the left-branching compounds – this advantage vanishes in later processing: the time or the number of fixations required to read the last two constituents C2C3 in condition *None* is no different from that observed for condition *Major*, $t(826) = -0.469$; $p > 0.1$. In gaze duration, the difference between conditions *None* and *Major* almost reverses with shorter reading times for *None* than for *Major*. This difference is close to significance, $t(910) = 1.97$, $p = 0.057$, and is mainly triggered by a higher skipping percentage of C1 and C2C3 for *None* than for *Major* (*None*: 37% for C1, 19% for C2C3; *Major*: 29% for C1, 4% for C2C3, cf. Inhoff & Radach, 2002). Right-branching compounds in condition *Minor*

Table 3. *Eye fixation measures as a function of presentation style for right-branching Dutch compounds*

Eye fixation measure	Compound presentation style		
	Concatenated (*zaalvoetbal*)	Major boundary (*zaal-voetbal*)	Minor boundary (*zaalvoet-bal*)
Gaze Duration	503	545	654
SubgazeC1	341	310	331
SubgazeC2C3	329	331	381
NrFixC1	1.30	1.17	1.21
NrFixC2C3	1.38	1.35	1.57

do not differ from those in condition *None* in subgaze duration for constituent C1, but they show longer durations and greater numbers of fixations than conditions *None* and *Major* in the processing of the C2C3-constituent cluster, all $ps < 0.01$ after Bonferroni correction.

Additional variables. We found a number of other variables to correlate with our dependent measures. We briefly report them here, without going into much detail in interpreting them. First, we observed a positive correlation of *WordLength* with gaze duration (Fig. 2, Panel A): the effect was non-linear and reached its ceiling for 18–22 character-long compounds. Second, there was an effect of branching: compounds with right-branching structure (*zaal/voetbal*) were processed faster than left-branching compounds (*voetbal/bond*, see Fig. 2, Panel B). This effect was most probably caused by the higher average C2C3-frequency in right-branching compounds than the C1C2- frequency in left-branching compounds (see Table 1). Third, higher-frequency compounds elicited shorter gaze durations (as well as selective regression path durations and total fixation times). Compound frequency interacted with the family size of the first constituent (*voet* in *voetbalbond*, see Fig. 2, Panel C), such that the negative effect of compound frequency on reading times was maximal in compounds with the smallest family, it decreased in compounds with relatively large families and reversed to a positive effect for compounds with the largest first constituent family. This effect replicates the interaction of compound frequency by family size reported for Dutch compounds by Kuperman *et al.* (2009) and shows that the role of properties of a compound as a whole (e.g., compound frequency) is attenuated when constituents are lexically entrenched (e.g., constituents with a high frequency of occurrence or those with a large morphological family).

Discussion

The results for both left-branching and right-branching compounds show that inserting a hyphen at the major constituent boundary is a two-edged sword. Early processes seem to benefit from the hyphen, as witnessed by shorter subgaze C1C2 durations in left-branching and shorter subgaze C1 durations in right-branching compounds in comparison to the concatenated compounds (see Inhoff *et al*., 2000, and Juhasz *et al*., 2005, for similar results with the space). In contrast, later processes seem to be disrupted, as witnessed by the larger number of fixations and/or longer subgaze durations and/or lower skipping rates obtained for the right side of the triconstituent compounds. The former result is in line with our hypothesis that the hyphen at the major constituent comes to aid in segmentation and in assigning the right hierarchical morphological structure. The latter result can, as speculated in the introduction, most likely be ascribed to the illegality of spelling of hyphenated compounds.

Overall we conclude that spelling illegality does not pose a major barrier for processing of Dutch triconstituent compounds with hyphens at the major constituent boundary. However, it should be noted that in the first half of the experiment reading performance is still better for concatenated compounds than for these hyphenated compounds. Interestingly, in the course of one experiment, readers seem to adapt to illegal hyphenation at the major constituent boundary so that in the second half of the experiment they have improved so much that performance of readers in recognizing these compounds is on par with their performance in recognizing conventionally spelled concatenated compounds (see Fig. 2, Panel D). In contrast, the spurious segmentation elicited by placing the hyphen at the minor constituent boundary was detrimental to compound processing throughout the experiment (be it that also for this presentation style there is improvement towards the end of the experiment). It thus seems that including a hyphen at the minor boundary generates problems for detecting the hierarchical morphological structure and for integration of all constituents into a unified meaning.

EXPERIMENT 2

One reason that Dutch readers have some problems with hyphenation in compounds – especially in the initial part of the experiment – may be that they are not all that familiar with hyphenated compounds. That is, even though hyphenated compounds are not completely alien to Dutch, as hyphens are for instance used in compounds where one part is a number or letter (*79-jarige* ''79-year old person'', or *t-shirt*), for several reasons they occur less frequently than in the language of our second experiment, Finnish. As in Dutch, Finnish spelling conventions prescribe that a hyphen needs to be inserted in compounds when one constituent ends with the same vowel as the next constituent begins with. One of the reasons hyphenation is more common in Finnish than in Dutch is that Finnish has more words ending in vowels, partly inspired by the fact that Finnish has a less extensive consonant register (in Finnish only 13 consonants are in regular use, whereas in Dutch there are 20). In addition, the new Dutch spelling rules of 1996 prescribe that the interfix -e- in words like *eende-ei* ''duck egg'' should be replaced with -en-, so that a lot of candidate compound words for hyphenation ended up with a consonant in the middle expelling the need to insert a hyphen (*eendenei).*

Moreover, it should be noted that compounding in Finnish is very productive – even more productive than in Dutch (see Moscoso del Prado Martín *et al*., 2004) – due to which the number of multiconstituent compounds is considerable. Probably considering the fact that heavy compound clusters are not always easy to deal with, writers of Finnish sometimes opt to insert hyphens at major constituent boundaries, even though spelling regulations prescribe otherwise. In our Finnish database (Laine & Virtanen, 1999) covering 2.5 years of articles of the second biggest newspaper in Finland (Turun Sanomat), we therefore find words such as *palvelutuotanto-yksikkö* ''serviceproduction-unit''. In general, our Finnish database comprises about 1.5 million word types of which more than 50% are compound words and about 5% of these compounds (38,940 in number) include one or more hyphens. The CELEX lexical database for Dutch counts about 75,000 lemma types, of which some 20% (about 16,000) are compounds. About 3% of these compounds (394 types) include one or more hyphens. Given the fact the Finnish readers are more used to hyphens in compounds than Dutch readers, we predict that hyphenation is less detrimental to compound processing in Finnish. This prediction could materialize in such a way that in the beginning of the experiment a hyphen inserted at the major constituent boundary would not disrupt triconstituent compound reading (as it did in Dutch) and that in the end of the experiment a solid facilitation effect is observed.

Another issue that we will take up in the second experiment is the effect of hyphenation in compounds that do not have a clear left-branching or right-branching structure. For instance, a word like *koulu/kirja/kauppa* ''schoolbookshop'' includes existing compounds at both sides of the word (schoolbook and bookshop) and it may equally well refer to a ''bookshop at the school area'' as to a ''shop where one sells schoolbooks'. We included ambiguous compounds like this with on average a similar C1C2-frequency and C2C3-frequency in sentences with a neutral beginning, so that both options of compound reading are viable upon encountering the compound. Inserting a hyphen in these ambiguous compounds with an unclear hierarchical structure provides an interesting test case as to whether there are any structural preferences in assigning left-branching or right-branching structure to triconstituent compounds. If a reader would typically extract first constituent information as quickly as possible and try to use that as the modifier of the remaining cluster, inserting a hyphen between the first and second constituent (school-bookshop) should be facilitative in comparison to inserting a hyphen between the second and third constituent (schoolbook-shop). If on the other hand integration of constituents is attempted as soon as two of them have been identified, one may expect that ''school-book-shop'' is easier to deal with than school-bookshop.

Method

Participants. Thirty-seven students of the Turku University participated in this experiment for two cinema tickets. All were native speakers of Finnish and had normal or corrected- to-normal vision.

Apparatus. As in Experiment 1, eye movements were recorded with an EyeLink II eyetracker manufactured by SR Research Ltd (Canada). The eyetracker had the same properties and was used with the same recording parameters as those described in Experiment 1.

Materials. The set of target words comprised 138 Finnish left- or right-branching triconstituent compounds. Of these compounds, 84 were left-branching (e.g., *lentokenttätaksi* ''airport taxi''), 54 were right-branching (e.g., *salijalkapallo* ''indoor football''). As in Experiment 1 the main factor of interest for the clearly branching compounds was compound presentation style, *CmpPresStyle*, including three levels: *None* (e.g., *lentokenttätaksi, salijalkapallo*), *Major* (e.g., *lentokenttä-taksi, sali-jalkapallo*) and *Minor* (e.g., *lento-kenttätaksi, salijalka-pallo*). Note that also in Finnish the insertion of hyphens is against prescribed spelling conventions. For the left-branching compounds, the incorporated compound at the left side (e.g., *lentokenttä* in *lentokenttätaksi*) had an average frequency of about 17 occurrences per million, but had a non-existing or very low-frequency compound (*kenttätaksi* ''port/field taxi'') at the right side (average frequency 0.003 per million). For the right-branching compounds, the incorporated compound at the right side (*jalkapallo* in *salijalkapallo*) had an average frequency of about 42 per million, but a non-existing or very low-frequent compound (*salijalka* ''indoor foot'') at the left side (average frequency 0.01 per million). With respect to the unequal distribution of left-branching and right-branching Finnish compounds in the experiment, it should be noted that – as in Dutch – left-branching compounds are more common than right-branching ones, so again we follow the distribution of triconstituent compounds in the language at large.

In addition to the clearly branching compounds, 54 ambiguous compounds were included which were neither clearly left-branching nor right-branching (e.g., *koulukirjakauppa* ''schoolbookshop''). Also here the main factor of interest was compound presentation style, *CmpPresStyle*, including three levels: *None* (e.g., *koulukirjakauppa*), *Left* (e.g., *koulu-kirjakauppa*) and *Right* (e.g., *koulukirja-kauppa*). Here the incorporated compound at the left side (*koulukirja* in *koulukirjakauppa*) had an average frequency of about 9.3 per million, which was approximately the same as the frequency of the incorporated compound at the right side, 12.4 per million. We chose to analyze the ambiguous compounds separately from the clearly branching ones. Lexical statistical properties of all target compounds of Experiment 2 can be found in Table 4.

As in Experiment 1, each target word was embedded in a separate sentence and never occupied the sentence-initial or sentence-final position. No sentence was longer than one line of text (82 characters). For the clearly branching compounds, three stimulus lists were prepared so that a given compound word appeared in the *None*-condition in the first list, in the *Major*-condition in the second list and in the *Minor*-condition in the third list. There were 138 clearly branching compounds in each list with 46 compounds for each presentation style (28 left-branching, and 18 right-branching). Each list also included 54 ambiguous compounds, 18 in each presentation style (*None*, *Left*, or *Right*). The presentation of the stimulus lists was counterbalanced across participants, such that each participant saw a given compound only in one condition. The sentences were displayed one at a time starting at the central-left position on the computer screen. Stimuli were presented in fixed-width font Courier New, size 12. With a viewing distance of about 80 cm, one character space subtended approximately

Table 4. *Lexical-statistical properties (ranges in parentheses) of the Finnish triconstituent compounds with properties of left-branching, right-branching and ambiguously branching compounds separately (Experiment 2)*

	Compound type			
	All	Left-branching	Right-branching	Ambiguous branching
N	192	84	54	54
Example	–	*lentokenttätaksi*	*salijalkapallo*	*koulukirjakauppa*
Whole word frequency[a]	0.8 (0.1–9.5)	0.8 (0.1–7.6)	1.3 (0.1–9.5)	0.4 (0.1–4.8)
1st constituent frequency[a]	326 (0.4–1955)	319 (0.7–1855	325 (0.2–1629)	336 (0.4–1955)
2nd constituent frequency[a]	362 (0.4–6452)	296 (0.4–1970)	585 (1.0–6452)	241 (16–1186)
3rd constituent frequency[a]	316 (1.5–3494)	229 (1.5–1463)	367 (8.1–1629)	400 (3.1–3494)
Frequency 1st and 2nd constituent together[a]	10 (0–144)	17 (0.1–144)	0.003 (0–0.6)	9 (0.2–63)
Frequency 2nd and 3rd constituent together[a]	15 (0–288)	0.003 (0–0.4)	42 (0.1–288)	12 (0.2–185)
Word length[b]	15.8 (13–24)	16.0 (13–23)	15.4 (13–24)	16.0 (13–22)
1st constituent length[b]	5.1 (3–9)	4.9 (3–9)	5.5 (3–9)	5.0 (3–8)
2nd constituent length[b]	4.9 (3–11)	5.0 (3–11)	4.5 (3–8)	5.3 (3–9)
3rd constituent length[b]	5.8 (3–11)	6.1 (3–11)	5.3 (3–9)	5.8 (4–9)

[a] per million; [b] in characters.

0.36° of visual angle. In addition to the 192 target sentences, there were 70 filler sentences. Sentences were presented in two blocks: the order of sentences within the blocks was pseudo-randomized and the order of blocks was counterbalanced across participants. Approximately 15% of the sentences was followed by a yes-no question pertaining to the content of the sentence. The experiment began with a practice session consisting of 8 filler sentences and 3 questions.

Procedure. The procedure was the same as in Experiment 1.

Dependent variables, predictors and statistical considerations. Dependent variables, predictors and statistical considerations were identical to those described above for Experiment 1. As in Experiment 1, our main interest is how the presentation format (*CmpPresStyle*) of compounds affects triconstituent compound processing and how it interacts with item position (*TrialNum*). As noted above, we explored these issues separately for clearly branching compounds and ambiguous compounds. We start off with presenting the analyses of the clearly branching compounds.

Results and discussion for clearly branching compounds

We used the same criteria to exclude fixations from further analyses as in Experiment 1, yielding a data pool that consisted of 6,411 data points. The model for gaze duration revealed a pattern that is similar to that observed in Experiment 1, in that Finnish compounds presented in condition *Minor* were processed slower than those in conditions *None* and *Major* (ps < 0.001 after Bonferroni correction). Unlike in Experiment 1, however, compounds with a hyphen at the major constituent boundary were processed faster than concatenated ones, $t(2986) = 2.57$, $p = 0.01$. The mean gaze durations per condition were: 738 ms in *None*, 706 ms in *Major*, and 810 ms in *Minor*. For the final model for gaze duration, we refer to Appendix 1.

Like in Experiment 1, gaze durations for compounds in conditions *Major* and *Minor* were shortened towards the end of experiment significantly more than gaze durations for concatenated compounds in condition *None* (see Fig. 3). The same interaction of presentation format by position in the list was observed in the selective regression path duration and total fixation time, such that reading times for compounds in conditions *Major* and *Minor* were shortened more than the reading times for concatenated compounds.

Panel D in Fig. 3 indicates that the processing speed of compounds in condition *Major* and *None* is similar in the beginning of the experiment, while compounds in condition *Major* develop a sizable processing advantage over concatenated compounds in the course of the experiment. The learning improvement is similar for compounds in the *Major* and *Minor* conditions, and is not observed in condition *None*. This pattern is fully supported by the two-tailed t-tests that revealed no difference in gaze durations across conditions *Major* and *None* in the first half of the experiment (positions 1–150 in the experimental list: 739 ms for *None* and 718 ms for *Major*, $t(1361) = 1.09$; $p = 0.27$), and showed a significant benefit for *Major* in the second half of the experiment (positions 151 onwards; 738 ms for *None* and 695 ms for *Major*,

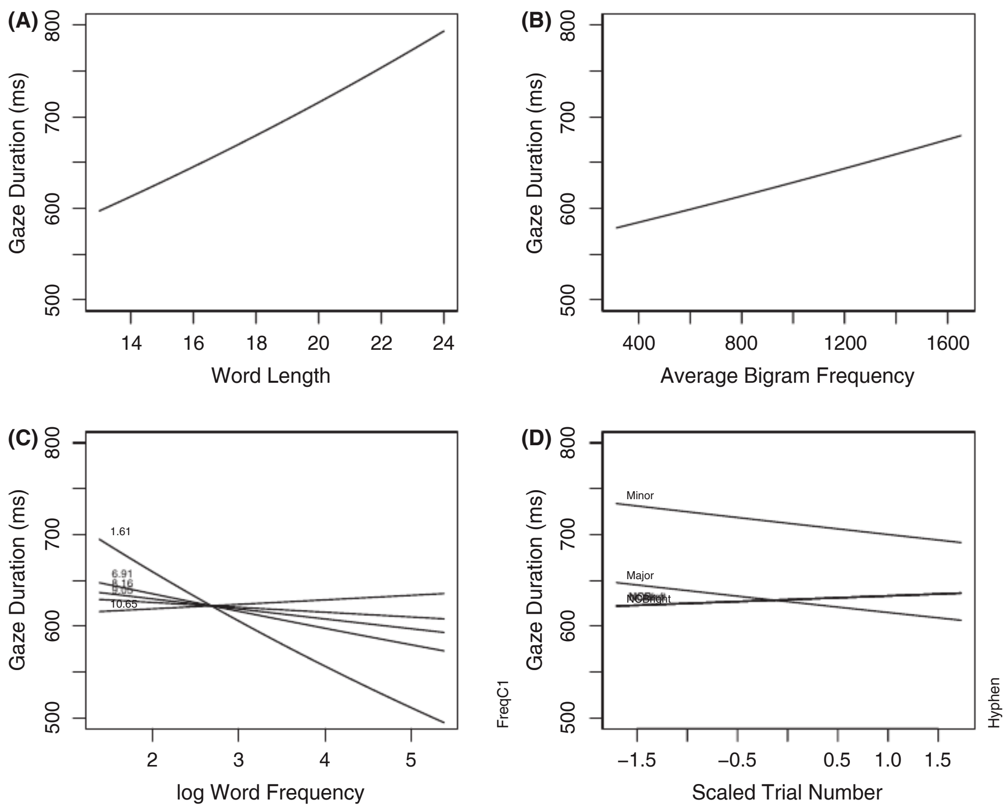

Fig. 3. Partial effects on gaze duration in Experiment 2 of: (A) word length; (B) average bigram frequency; (C) the interaction of compound frequency by first constituent frequency – the effect of compound frequency is plotted for quartiles of first constituent frequency (values shown at the left margin), compound frequency has the strongest negative effect, when the first constituent is the least frequent; the effect decreases as the first constituent frequency increases, and becomes weakly positive for compounds with the highest-frequency first constituent; (D) the interaction of standardized trial number by compound presentation style. There is a learning effect in conditions *Major* and *Minor*, but not in condition *None*.

$t(1620) = 2.53$; $p = 0.01$). The mean gaze durations for *Minor* were 832 ms in the first half and 791 ms in the second half of the experiment: in both halves, this condition elicited significantly longer gazes than *Major* and *None* (all *p*s < 0.001 after Bonferroni correction). Thus, as in Experiment 1, we observed adaptation to illegal hyphenation (conditions *Major* and *Minor*) even in such a short-term exposure as provided by the present experiment.[5]

However, there is also an important discrepancy between Experiments 1 and 2. In Experiment 1 the Dutch compounds with a hyphen at the major constituent boundary were initially processed slower than concatenated ones and were only processed equally fast as concatenated compounds at the latter part of the experiment. Conversely, there was no disruption of processing Finnish compounds with hyphenation at the major boundary in comparison to concatenated ones in the beginning of the experiment, and by the end of experiment there was a sizable processing advantage for them in comparison to concatenated compounds.

Detailed analyses of the hyphenation effect. Table 5 indicates that for Finnish like for Dutch left-branching compounds C1C2 subgaze duration is shortest with hyphenation at the major constituent boundary. This condition also elicits the lowest number of fixations on these constituents (NrFixC1C2). The multilevel regression models (with the Poisson link function for the fixation count measures) reveal that the difference between *Major* and *Minor* is significant for both measures (*p*s < 0.05; models not shown), the difference between *Major* and *None* is fully significant for the NrFixC1C2 and showing a tendency for SubgazeC1C2 ($p < 0.05$, $p < 0.10$, respectively; models not shown).

It should be noted that there is a significant speed-up in SubgazeC1C2 duration for *Major* compounds over time, but not for *None* and *Minor* compounds (interaction with *TrialNum* only significant for *Major* compounds, $p < 0.05$, but not for *None* and *Minor*, *p*s > 0.10). In contrast to Dutch, the advantage of *Major* in the processing of the C1C2-constituent cluster is *not* set off by slower recognition of C3 in comparison to concatenated compounds (condition *None*), In fact, SubgazeC3 durations and NrFixC3 are exactly the same for the *Major*, *None* and *Minor* condition (all *p*s > 0.10).

For right-branching compounds (see Table 6), SubgazeC1 is shortest for *Major* and longest for *Minor* compounds (for all contrasts, $p < 0.05$), a pattern that is reflected in NrFixC1 as well. Again, there is a significant speed-up in SubgazeC1 duration for *Major* compounds over time, but not for *None* and *Minor* compounds (interaction with *TrialNum*). This time the advantage of *Major* in the processing of the C1-constituent is set off by slower recognition of the C2C3-cluster in comparison to concatenated compounds (condition *None*), $p < 0.05$; the *None* condition is also faster than Minor compounds ($p < 0.05$). A similar pattern can be observed in NFixC2C3.

Table 5. *Eye fixation measures as a function of presentation style for left-branching Finnish compounds*

Eye fixation measure	Compound presentation style		
	Concatenated (*lentokenttätaksi*)	Major boundary (*lentokenttä-taksi*)	Minor boundary (*lento-kenttätaksi*)
Gaze Duration	730	702	754
SubgazeC1C2	501	437	518
SubgazeC3	272	273	276
NrFixC1C2	2.01	1.81	2.06
NrFixC3	1.17	1.14	1.17

Table 6. *Eye fixation measures as a function of presentation style for right-branching Finnish compounds*

Eye fixation measure	Compound presentation style		
	Concatenated (*salijalkapallo*)	Major boundary (*sali-jalkapallo*)	Minor boundary (*salijalka-pallo*)
Gaze Duration	684	659	819
SubgazeC1	324	286	358
SubgazeC2C3	337	365	375
NrFixC1	1.26	1.18	1.35
NrFixC2C3	1.42	1.50	1.58

Taken together, the more detailed data analyses show that the results for left- and right-branching compounds are quite similar in Dutch and Finnish. In both languages, both types of compounds benefit from hyphens at the major constituent boundary at early stages of processing. This indicates that the hyphen may play a beneficial role in segmentation and in the assignment of the right hierarchical morphological structure. It is notable that in both left-branching and right-branching Finnish compounds the average gaze durations are shorter for *major* compounds than for concatenated compounds, which is of course mostly due to the steady improvement throughout the experiment on processing the former but not the latter types of compounds.

Other effects. In our analysis of control variables, we observed that longer compounds came with slower processing, a well-established pattern obtained in visual word recognition (see Rayner, 1998). Also the average bigram frequency of compounds had an effect with higher average bigram frequencies yielding faster processing times (cf. Massaro & Cohen, 1994). Similarly to Experiment 1, we observed that the facilitative effect of compound frequency is at its strongest in compounds with the lowest-frequency first constituents (e.g., *herne/keitto/purkki* ''pea soup can''), while this effect is attenuated in compounds with higher-frequency first constituents and is even reversed to inhibitory for compounds with first constituents of the highest frequency (e.g., *kesä/mökki/elämä* ''summer cottage life''). This observation adds to the range of findings obtained in eye-tracking studies on Dutch and Finnish compounds (Kuperman *et al*., 2008, 2009), showing that lexically entrenched constituents (e.g., those with a high frequency of occurrence or those with a large morphological family) undermine the influence of the properties of compound as a whole (e.g., compound frequency), on the speed of compound recognition. The competition between a compound and its constituents in the process of complex word recognition follows straightforwardly from the assumptions of the multiple-route model of morphological processing, PROMISE (cf. Kuperman *et al*., 2008), which holds that there are several sources of information that contribute to compound word recognition and that the importance of one source may be modulated by the importance of another source.

Results and discussion for ambiguous compounds

The other question we set out to address is the processing of triconstituent compounds with an ambiguous branching structure (e.g., schoolbook-store vs. school-bookstore). The data set for the ambiguous compounds comprised 1,802 data points. Since major and minor constituent boundaries cannot be defined for such compounds, we selected three presentation formats: concatenated (*None*), hyphen inserted at the boundary between C1 and C2C3 (*Left*) and hyphen inserted at the boundary between C1C2 and C3 (*Right*). If hyphenation biases one of the possible interpretations of these ambiguous compounds, we may expect differential effects of presentation format on inspection times for those compounds.

Our expectations were not supported by any of the statistical analyses (gaze duration, SRPD, or total fixation time), as the models did not reveal significant contrasts between the three conditions (all ps > 0.05): Mean gaze duration of 748 ms for *None*, 751 ms for *Left*, and 738 ms for *Right*. Apparently, readers are not sensitive to whether a hyphen is present or in what position it is present when processing compounds with ambiguous branching. Also, there were no significant interactions with trial number in any of the models (all ps > 0.05). The main factors that did affect ambiguous compound processing were word length and word frequency. As argued above, inserting hyphens in compounds with an unclear hierarchical structure provides an interesting test case as to whether there are any structural preferences for left-branching or right-branching compounds. If there would be a structural preference for a hyphen at the left side as in *school-bookstore* this may indicate that readers have a preference for right-branching structures; if there would be a structural preference for a hyphen at the right side as in *schoolbook-store*, this may indicate that readers have a preference for left-branching structures. In other words, the hyphen could enable a reader to figure out the preferred hierarchical structure more quickly. The results indicate that this is not the case. Instead it seems that readers are quite pragmatic in making use of the hyphen, probably interpreting the compound as right-branching when the hyphen is at the left side and as left-branching when the hyphen is at the right side. This was probably inspired by the fact that the compounds were embedded in sentences with a neutral beginning, so that both options of compound reading were viable upon encountering the compound. Had we used biasing contexts, we would have more or less created a minor and major constituent boundary in the ambiguous compounds, perhaps leading to similar results as for the clearly branching compounds. However, in that case we would not have been able to test whether there are structural preferences in assigning hierarchical structure. One may thus conclude that there is no structural preference in interpreting ambiguous compounds or, to put it differently, that both the constituent boundary at the left and the right side may serve as the major constituent boundary in such compounds. It should be noted that Pollatsek *et al*. (2010) found a different result for triconstituent ambiguous English derivations such as *unlockable* (which can be interpreted as *un-lockable* or *unlock-able*) than we did for triconstituent ambiguous compounds. Their results favored a left-branching structural interpretation but they note that this is likely due to a general higher frequency of left-branching than right-branching structures in case of English derivations.

GENERAL DISCUSSION

In this study, we investigated whether inserting hyphens in normally concatenated triconstituent compounds facilitates the segmentation process and affects the speed with which they are processed. There are several findings that need to be discussed. First, for Dutch (Experiment 1) and Finnish triconstituent compounds (Experiment 2) we found that compounds with hyphens at the minor constituent boundary (e.g., *zaalvoet-bal* ''indoorfoot-ball'' and *lento-kenttätaksi* ''air-porttaxi'') are processed slower than concatenated compounds (e.g., *zaalvoetbal* and *lentokenttätaksi*) and compounds with hyphens at the major constituent boundary (e.g., *zaal-voetbal* ''indoor-football'' and *lentokenttä-taksi* ''airport-taxi''). This difference can most probably be ascribed to the fact that a hyphen at the minor boundary gives a misleading cue with respect to the hierarchical morphological structure of the compound. For instance, in case of *zaalvoet-bal* ''indoorfoot-ball'' it prompts a reader to integrate the first and second constituent, leading to a semantically highly implausible concept that subsequently should serve as a modifier for the third constituent. In other words, we argue that the slower processing times for compounds with hyphens at the minor constituent boundary are due to the extra time it takes to overcome the initially incorrect assignment of hierarchical morphological structure, leading to an incorrect semantic interpretation of the compound.

Second, in the introduction, we speculated that inserting a hyphen at the major constituent boundary may be a double-edged sword. On the one hand, it may come to aid in segmentation. On the other hand, since inserting a hyphen goes against the current Dutch and Finnish spelling conventions, it may disrupt compound processing, especially in later stages. Both predictions are supported by our data. With respect to the segmentation issue, the subgaze analyses in Dutch and Finnish showed that for both left-branching and right-branching compounds, subgaze durations at the left side of the major constituent boundary are shorter for hyphenated than for concatenated compounds. This, to our minds, indicates that it is easier to parse out the initial part of these hyphenated compounds than to parse out the initial part of concatenated compounds. However, the subgaze analyses also showed a processing advantage for concatenated compounds in comparison to hyphenated compounds at later measures in both Finnish and Dutch, indicating that the reader may be slowed down by the spelling illegality introduced by inserting a hyphen.

Third, in both experiments we found a greater learning effect for both types of hyphenated compounds than for concatenated compounds. This confirmed our hypothesis that participants would have to get used to illegally spelled compounds before coming up with (or at least approaching) a more optimal way to process them. However, even in the latter part of the experiments compounds with hyphens at the minor constituent boundary are processed slower than both concatenated compounds and compounds with hyphens at the major constituent boundary, indicating that it is hard to neglect a cue that points to an incorrect hierarchical morphological structure. In contrast, for compounds with illegal hyphenation at the major boundary it seems that even within a single experiment readers may improve performance to such an extent, that they perform equally well (as in Dutch) or even better (as in Finnish) than on compounds that are spelled correctly.

Fourth, we found a discrepancy between the Dutch and Finnish results. For compounds with a hyphen at the major constituent boundary we found disruption in reading (in comparison to reading concatenated compounds) in the first part of the Dutch experiment. For the second half of the experiment there was no difference in processing time between the two compound presentation formats anymore. For Finnish, inserting a hyphen at the major constituent boundary was not disruptive to compound processing at all. That is, in the beginning of the experiment such compounds were processed equally fast as concatenated compounds, whereas in the latter part of the experiment they were processed even faster. This discrepancy points to cross-linguistic differences in spelling conventions and experiences with the hyphen as a punctuation mark. Even though hyphens are currently allowed in some orthographic contexts in both Dutch and Finnish, we argued above that Finnish readers get more exposure to hyphenated compounds due to the higher prevalence of hyphenated compounds in Finnish than in Dutch. Given that Finnish readers are more often exposed to hyphenated compounds, it is likely that illegally inserted hyphens are easier to overcome for Finnish than for Dutch readers.

In an article in Finland's largest newspaper *Helsingin Sanomat* a few years ago, it was suggested that many long compound words in Finnish could be read with more ease if they were to be presented with a hyphen at a constituent boundary (see Fig. 4). With long compound words the authors were referring to compounds with three or more constituents. The article suggested to change the presentation format of these kinds of compounds by inserting hyphens at major constituent boundaries, thus after the first constituent in s*ali-jalkapallo* ''hall-football'' and after the second in *jalkapallo-liitto* ''football-association''. In fact, the idea for this study was directly derived from that newspaper article. As we have shown, it would make sense to follow this suggestion as it would come with a reduction in the processing speed of such compounds. Moreover, the current study shows that getting used to such a spelling change does not need a great number of exposures or years of adjustment.

In summary, the current study shows that morphological constituents play a major role in triconstituent compound processing. It also shows that one of the major tasks in processing such compounds is to assign the correct hierarchical morphological structure to them. The assignment of the correct structure can be facilitated when an explicit visual cue as the hyphen is inserted at the major constituent boundary, even though the insertion of this cue goes against spelling regulations. The current study thus also indicates that spelling violations may increase processing speed as long as they facilitate identification of the word structure and are semantically interpretable.


HELSINGIN SANOMAT 10.10.2006

MIELIPIDE

'Compound word spelling should be renewed'

Yhdyssanojen kirjoitustapaa uusittava

Yksi tapa helpottaa lukemista on lyhentää sanoja. Niinpä ehdotamme väliviivojen käytön lisäämistä yhdyssanojen jakamiseen.

'One way to make reading easier is to shorten words. To that end, we propose to increase the use of hyphenation in order to split up compound words'

Fig. 4. Title and excerpt from an opinion article in the *Helsingin Sanomat* (Finland's biggest newspaper) with the suggestion to use hyphens at major constituent boundaries in long Finnish compounds in order to facilitate reading.

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NOTES

[1] We use the forward slash to indicate constituent boundaries.

[2] The hyphenation is legal here, since Finnish spelling rules prescribe that compounds should be hyphenated when the first constituent ends with the same vowel as the second constituent begins with.

[3] It should be noted that in Dutch (but not in Finnish) the spelling regulations prescribe that hyphens are allowed to be inserted in complex compound clusters, if the writer suspects that a reader may run into difficulties when reading the compound (e.g., in tweederangsonderwijs ''second-rate education'', a hyphen may be inserted after the second constituent, tweederangs-onderwijs, in order to facilitate its comprehension). However, this rule is fully unknown to most Dutch language users and therefore hardly ever used in real life.

[4] Perhaps this is also the reason that research on triconstituent complex words in general has been rare. One of the consequences is that there is no clear theoretical account on how trimorphemic words are processed.

[5] We would like to point out that the positive effects of the hyphen (both in terms of the learning effect for both types of hyphenated compounds and how fast compounds with hyphens at the major boundary are processed in both languages) are even more convincing, if one considers the fact that in our experiments the hyphens do not provide a consistent cue in indicating hierarchical morphological structure. That is, since half of the time the hyphen is at the minor constituent boundary and half of the time at the major constituent boundary, the hyphenation cue remains ambiguous throughout the experiments. Given that – even under these circumstances – participants take benefit from the hyphen and/or adapt to it rapidly, it could be predicted that if hyphens are used in an unambiguous way, processing benefits would be even greater. We leave this issue for future investigation.

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APPENDIX 1

Final models for Experiment 1 and 2 with random and fixed effects presented separately. Only those fixed effects or interactions, and random effects are reported that significantly ($p < 0.05$) improved the model's performance as indicated by the likelihood ratio model comparison tests. *T*-values below −2.0 and above 2.0 roughly correspond to *p*-values below 0.05. Where supported by the model comparison tests, non-linear effects are reported. If an interaction was found significant, its main effects are reported as well: we note that these effects are not independently interpretable in the lmer() output.

Table A1. *Experiment 1, Gaze duration model: random effects*

Groups	Name	Variance	Std.Dev.	Corr
Word	(Intercept)	0.0120	0.1097	
	SexMale	0.0166	0.1289	0.013
Subject	NumWord	0.0006	0.0239	
Subject	TrialNum	0.0019	0.0441	
Subject	famSecond	0.0010	0.0318	
Subject	(Intercept)	0.0725	0.2692	
Residual		0.1282	0.3581	

Table A2. *Experiment 1, Gaze duration model: fixed effects*

	Estimate	Std Error.	*t*-value
(Intercept)	4.5540	0.3254	13.99
WordLength,Linear	0.1997	0.0415	4.81
WordLength,Quadratic	−0.0050	0.0013	−3.77
BranchingRight	−0.1441	0.0278	−5.18
Major	0.0451	0.0225	2.01
Minor	0.1358	0.0227	5.99
TrialNum	−0.0045	0.0158	−0.28
famFirst	−0.1051	0.0267	−3.94
WordFreq	−0.0394	0.0138	−2.86
Major:TrialNum	−0.0601	0.0183	−3.28
Minor:TrialNum	−0.0379	0.0185	−2.05
famFirst:WordFreq	0.0196	0.0095	2.06

Table A3. *Experiment 2, Gaze duration model: random effects*

Groups	Name	Variance	Std.Dev.	Corr
Word	(Intercept)	0.0540	0.2323	
	SexMale	0.0200	0.1415	−0.802
Subj	(Intercept)	0.0825	0.2872	
Subj	TrialNum	0.0023	0.0477	
Residual		0.0892	0.2987	

Table A4. *Experiment 2, Gaze duration model: fixed effects*

	Estimate	Std. Error	*t*-value
(Intercept)	6.1910	0.1372	45.12
WordLength	0.0304	0.0039	7.84
FreqC1	−0.0337	0.0128	−2.63
WordFreq	−0.1367	0.0422	−3.24
Major	−0.0147	0.0208	−0.70
Minor	0.1168	0.0209	5.58
TrialNum	0.0073	0.0116	0.62
AverBigram	0.0002	0.00004	4.19
FreqC1:WordFreq	0.0136	0.0052	2.62
Major:TrialNum	−0.02626	0.0121	−2.17
Minor:TrialNum	−0.02487	0.0122	−2.05