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OBSERVATION

Readers Use Word Length Information to Determine Word Order

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It is assumed by the OB1-reader model that activated words are flexibly associated with spatial locations. Supporting this notion, recent studies show that readers can confuse the order of words. As word position coding is assumed to rely, among other things, on low-level visual cues, OB1 predicts that it must be harder to determine the order of words when these are of equal length, and consequently, that it is more difficult to read uniform word length sentences. Here we review recent evidence, obtained by our peers, in line with this prediction. We additionally report an analysis of eye-movement data from the GECO corpus, replicating the phenomenon in a natural reading setting, and an experiment revealing a negative impact of length uniformity in a grammatical decision task. By virtue of the spatiotopic sentence-level representation, OB1-reader is currently the only model of reading to account for these behaviors.

Public Significance Statement
Successfully recognizing the order of words in sentences is just as important as recognizing the order of letters in words. However, much less is known about the former process than the latter process. Here we report the observation that cues about word length play a role in word position coding.

Keywords: reading, word position coding, grammatical processing, syntactic processing, visual word recognition

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The phenomenon illustrated in Figure 1 implies several interesting things. Foremost, the perception of word order is not as straightforward as might have been previously thought. Dominant theories of reading have long assumed that words are processed strictly one-by-one (e.g., Reichle et al., 1998), which would make the perception of word order a given. The fact that it is *not* a given (hence Figure 1) suggests either that recognized words must be stored in a postlexical buffer from where they are flexibly associated with locations in a sentence representation (see, e.g., Huang & Staub, 2021, 2022), or that words are processed in parallel (see Mirault et al., 2022, for discussion).

Irrespective of whether words are processed serially or in parallel, it has in recent years become clear that models of reading should comprise mechanisms for flexibly coding the positions of words. At present, the only model that does so is the OB1-reader model (Snell, van Leipsig et al., 2018). This model predicted transposed-word (TW) effects through the assumption of a spatiotopic sentence-level representation, onto which simultaneously activated words are mapped with the help of top-down expectations and bottom-up visual cues. Thus far, most of the evidence in support of this assumption has specifically underpinned the contribution of top-down (syntactic) expectations. Indeed, in the example of Figure 1, the transposed words are approximately of equal length, so here low-level visual cues (e.g., word lengths) are unlikely to play a role. Experimental studies of the phenomenon similarly emphasized that the perception of word order is dictated by syntactic constraints (Liu et al., 2020; Mirault et al., 2018; Snell & Grainger, 2019a; Wen et al., 2021).

In the present paper, we shift our focus away from syntactic constraints and instead address the hypothesized contribution from low-level visual cues in the process of associating words with locations. The general idea, formalized in OB1, is that the first glance at a sequence generates knowledge about the number of to-be-recognized words in the visual field, along with their respective lengths. Upon viewing the sequence "My mother," for example, the model would expect a short word followed by a longer word; and upon having activated the representations "my" and "mother," these would therefore be mapped onto the first and second location, respectively. Such knowledge especially comes in handy when syntactic cues are lacking. Consider, for instance, the sequences "My little fluffy dog" and

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We adhere to open science practices. All data can be accessed at https://osf.io/4wmre/.

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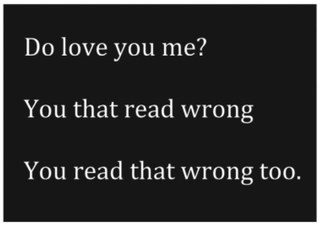
Figure 1
The "Do love you me" Phenomenon, Studied by Snell and Grainger (2019a)



"My big fluffy dog." In both sequences, the middle two words are of the same syntactic category, so here the location of "fluffy" cannot be discerned through syntax alone. OB1 predicts, then, that the second sequence is more likely to be perceived correctly than the first sequence, because "big" and "fluffy" can be dissociated by their lengths, whereas "little" and "fluffy" cannot. More broadly speaking, the process of mapping words onto locations—and thus reading speed on the whole—should deteriorate in the absence of visual cues to resolve ambiguity. These are the central hypotheses of the present study.

The remainder of this paper is structured as follows. Firstly, we will review important studies of Cutter et al. (2017, 2018), which happen to be in line with OB1's predictions. Next, we report an analysis of the GECO book reading corpus (Cop et al., 2017), showing that—in a natural reading setting—sequences with uniform word lengths demand more processing time than sequences with nonuniform word lengths. Finally, we report an experiment suggesting that length uniformity negatively impacts the processing of grammar.[1]

Reduced Naturalness

The main aim of Cutter et al. (2017, 2018) was tangential to ours. They investigated whether readers' preferred saccade length[2] is fixed or flexible. Upon exposing readers to sentences comprising exclusively 3-, 4-, or 5-letter words, they observed various eye-movement patterns indicative of modulations in the preferred saccade length, depending on the word lengths at hand. This led them to argue against the traditional notion that these systematic amplitudes are a direct function of readers' accumulated past experiences (Engbert & Krügel, 2010; McConkie et al., 1988).

A by-product of their investigation, which they relegated to an Appendix, is of particular relevance here. They reported that reading times increased significantly when readers were exposed to uniform length sentences, as compared to variable word length sentences. The authors' own account of this particular result was that uniform word length sentences were rated as being "less natural" than the variable word length sentences. Although there was nothing wrong with this explanation per se, the underlying cause of this reduction in perceived naturalness, from a cognitive point of view, remained obscure. That is, it is not clear whether participants cast their judgments on the basis of low-level visual factors (do uniform word length sentences simply look atypical?), or unforeseen semantic factors (one example of a uniform word length sentence was: "David often plays awful death metal music about Satan"), or perhaps a combination of these things.

OB1's account of increased reading times for uniform word length sentences is concrete: the mapping of activated words onto locations (thought to be a key aspect of the reading process) is slowed due to a lack of bottom-up visual cues. OB1 is agnostic about whether this may have instilled a sense of "unnaturalness" (note that the accounts of Cutter et al. and OB1 are not mutually exclusive); but, regardless, Cutter et al.'s studies marked the first behavioral evidence for a relationship between length uniformity and sentence processing speed, as predicted by OB1.

Incited by these initial insights, we were to establish the same phenomenon in a natural (book) reading setting.

An Analysis of the GECO Book Reading Corpus

The *GECO* corpus of Cop et al. (2017) comprises eye-movement data from 32 participants reading an entire book.[3] It has proven to be an excellent platform for investigating a variety of things, ranging from orthographic and morphological processing (e.g., Snell, Grainger, & Declerck, 2018) to the processing of sentence structures (e.g., Snell & Theeuwes, 2020). Concerning the latter, it was found that repeatedly encountering a given combination of word lengths (e.g., a 3-letter word followed by a 6-letter word followed by a 4-letter word) led to improved linguistic and oculomotor processing. Specifically, repeatedly encountering a certain combination (irrespective of linguistic content) led to reduced fixation durations, fewer fixations, and fewer corrective saccades. Importantly, these effects went beyond general task practice (Snell & Theeuwes, 2020), and provide additional support for the claim of Cutter et al. (2017, 2018) that the oculomotor system flexibly adapts to low-level visual regularities in the text at hand.

For their analysis, Snell and Theeuwes (2020) isolated sentences comprising at least four words, and labeled the first four words of these sentences on the basis of word length (e.g., a sentence starting with "Upon meeting his fiancé…" would get the label *4-7-3-6*). Here we adopted a similar approach, whereby structures with labels such as *4-4-4-4* and *3-3-3-3* were marked as being uniform.[4] We must note here that only a very small proportion of structures had uniform word lengths: in the Dutch version of the book (read by 18 Dutch-English bilingual participants), 29 out of 1,942 sentences had uniform word lengths; in the English version (read by 14 English monolinguals), 21 out of 2,140 sentences had uniform word lengths.

To assess whether a lack of word length variability makes reading more difficult, we analyzed the time spent looking at the four words (denoted as viewing time) and the number of fixations, as a function of whether the words had variable lengths. The analyses were carried out separately for Dutch and English readers. We employed linear mixed models (LMMs) with word length uniformity (*uniform* vs. *variable*) as a factor, average word length (known to influence

[1] We hereby declare that our study was not preregistered.

[2] First introduced by McConkie et al. (1988), the preferred saccade length refers to an apparent systematicity in the saccadic targeting process, whereby target locations more than seven letter spaces away from fixation tend to be undershot (i.e., the eyes land to the left of the target location) whereas target locations less than seven letter spaces away from fixation tend to be overshot (i.e., the eyes land to the right of the target location).

[3] The corpus can be accessed at https://expsy.ugent.be/downloads/geco/.

[4] As in Snell and Theeuwes (2020), the labeling and analyses only concerned the first four words of each sentence.

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processing speed) as a covariate, and by-participant intercepts and slopes as random effects. Values $|t| > 1.96$ were deemed significant. Prior to all analyses, we excluded instances where all words were skipped (8.00% of data points in the English data, 6.42% of data points in the Dutch data), and instances with a total fixation duration below 100 ms (0.20% of the remaining data points in English, 0.21% of the remaining data points in Dutch). We used Q–Q plots to check whether data were normally distributed. As this was not the case, we applied a log transformation and removed a few additional data points that deviated from the normal distribution, in English, three data points with log(fixation duration) > 8.81; in Dutch, two data points with log(fixation duration) > 8.61. In total, 8.18% and 6.62% of data points were excluded in English and Dutch, respectively.

Unsurprisingly, the average length of words had a very strong influence on both variables of interest, with longer and more fixations on longer words.[5] Despite the small proportion of data points belonging to the uniform word length condition (254 of 55,514 and 255 of 38,245 in English and Dutch, respectively), we obtained significant effects of length uniformity in both languages. In line with the hypothesis, length uniformity increased the time spent viewing the four words (in English reading, $b = 0.10$, $SE = 0.03$, $t = 3.07$; in Dutch reading, $b = 0.07$, $SE = 0.03$, $t = 2.31$). It also increased the number of fixations (in English reading, $b = 0.08$, $SE = 0.03$, $t = 2.66$; in Dutch reading, $b = 0.08$, $SE = 0.03$, $t = 2.75$). These effects are plotted in Figures 2 and 3. Note that the plotted data were weighted by the average lengths of words, as these were decidedly higher for the variable word length sentences (but statistical analyses were performed on log-transformed raw data).

As our two conditions (uniform vs. variable length structures) comprised quite disparate materials, we performed additional analyses on data that were matched as closely as possible on word length and frequency (calculated by averaging the lengths and frequencies of a structure's four words). Filtering was performed by sorting data points on word length and frequency, and then iteratively removing data points from the variable length condition until the average structure length and frequency within this condition matched that of the uniform length condition.

In English, after removing 39,231 data points (leaving us with 16,283 data points), the average word frequency of variable length structures matched that of uniform length structures ($M_{\text{variable}} = M_{\text{uniform}} = 6{,}016$ ppm), while the average word length was 3.40 letters (against 2.96 letters for uniform length structures). With further data point removal, we could have obtained a better match in terms of word length, but only at the cost of reintroducing a discrepancy in word frequency. In these filtered data, our hypothesized effect of length uniformity persevered: in viewing time, $b = 0.11$, $SE = 0.03$, $t = 3.36$; in a number of fixations, $b = 0.09$, $SE = 0.03$, $t = 3.06$.

Following the same procedure for Dutch, the optimal match between conditions was reached after removing 7,431 data points (leaving us with 30,814 data points, whereby frequency $M_{\text{variable}} = M_{\text{uniform}} = 4{,}492$ ppm), and average word lengths of 4.12 versus 3.08 letters for variable and uniform length structures, respectively. The detrimental impact of uniformity again persevered: in viewing time, $b = 0.07$, $SE = 0.03$, $t = 2.28$; in a number of fixations, $b = 0.08$, $SE = 0.03$, $t = 2.81$.

The above results suggest that word length uniformity makes reading more difficult. Whereas we argue that this is due to difficulty in word position coding, one could alternatively argue that these effects are in fact syntactic in nature. Specifically, word length likely informs syntactic category to some extent (e.g., short words are likely to be articles), and length uniformity thus precludes knowledge about which words can be skipped (articles, for instance, are often skipped). As a test of this scenario we compared the skipping probability between our two conditions, reasoning that if the prime cause of our effects is indeed hampered syntactic recognition, the number of skips in the uniform length condition should be decreased. As it turned out, we found such a pattern in Dutch reading ($b = -0.22$, $SE = 0.05$, $t = -4.11$), but not in English reading ($b = -0.02$, $SE = 0.05$, $t = -0.46$).[6] Due to these equivocal results, at present, we have to remain agnostic about this particular scenario.

In short, we replicated the pattern observed by Cutter et al. (2017)—this time in a natural reading setting whereby uniform word length sequences were part of a broader context (i.e., a story). However, while these findings align with our theory, we must acknowledge that they do not directly prove the involvement of word position coding processes (hence the test of word skipping probability reported above). In order to provide more direct evidence, we reasoned that if the slowed processing of uniform word length sequences is true, as described by the OB1-reader model, due to a lack of bottom-up visual cues in word position coding, then length uniformity should negatively impact the processing of grammar, specifically, too. We turn now to a direct test of this hypothesis.

Testing the Impact of Length Uniformity on Grammatical Decisions

In an online experiment, we collected data from 42 French volunteering participants ($F = 23$) who reported to be at least 18 years old. All participants gave informed consent and were made aware that their data were stored and processed anonymously. Note that, because the experiment was run online, we had no control over participants' display settings or external environments.

The experiment was a grammatical decision task, implemented as a 2 × 2 design with grammaticality (the sequences to be judged were *grammatical* vs. *ungrammatical*) and length uniformity (sequences had *uniform* vs. *variable* word lengths) as factors. For each of the four conditions, we constructed 50 4-word sequences, whereby we ensured that the ungrammatical sequences could not be corrected through a transposition of two words. The average length of words was equal across conditions ($M = 5.00$ characters). Each sequence was shown once to each participant, meaning we carried out a total of 2,100 measurements per condition.[7] The data and stimuli can be accessed at https://osf.io/4wmre/. Ethical approval was provided by the ethical board of the Faculty of Behavior and Movement Sciences of the Vrije Universiteit Amsterdam.

Each trial started with a central fixation cross, the duration of which varied between 500 and 700 ms. The fixation display was

[5] Viewing time English: $b = 0.14$, $SE = 0.00$, $t = 70.34$; viewing time Dutch: $b = 0.14$, $SE = 0.00$, $t = 66.78$; nr. fixations English: $b = 0.15$, $SE = 0.00$, $t = 75.90$; nr. fixations Dutch: $b = 0.14$, $SE = 0.00$, $t = 70.86$.

[6] For these particular analyses, we included trials where all words were skipped. In English reading, we had to use a model without random slopes in order to ensure that it converged.

[7] This is well above the recommendation of Brysbaert and Stevens (2018) for having sufficient statistical power (1,200 measurements for a moderately sized effect).

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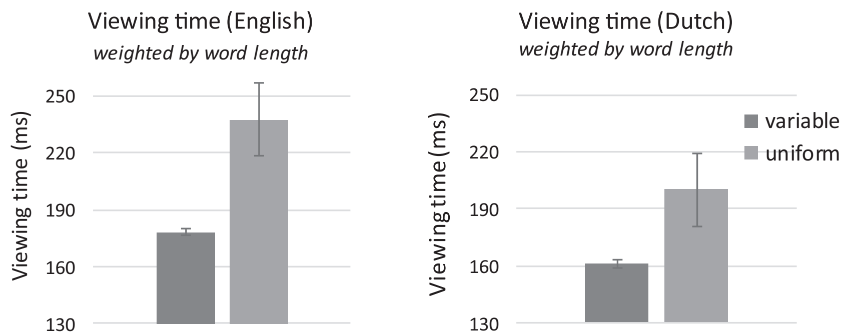
Figure 2

Sentences Viewing Times, Weighted by the Average Word Length



Note. Error bars depict standard errors.

followed by a 200 ms blank display, and subsequently, the 4-word sequence was presented in size 18 monospaced font. The sequence stayed onscreen until the participant pressed a right or left key for "grammatical" or "ungrammatical" respectively. Participants were instructed to answer as quickly and accurately as possible. Upon the response, a 500 ms green or red fixation dot provided positive or negative feedback, respectively. Eight practice trials preceded the experimental trials. The experiment lasted 10 to 15 min.

Response time (RT) and accuracy were analyzed with an LMM and a generalized LMM, respectively, with by-participant random intercepts and random slope for the length uniformity factor.[8] We removed trials for which $100 \text{ ms} < RT < 3{,}000 \text{ ms}$ (5.81% of trials), and only included correctly answered trials in the analysis of RTs (9.37% of the remaining trials). As with our previous analyses, data were log-transformed for the purpose of normalization.

In line with our hypothesis, we observed significant main effects of both grammaticality and length uniformity. Participants were faster and more accurate when processing grammatically correct (RTs: $b = 0.22$, $SE = 0.03$, $t = 7.11$; accuracy: $b = 1.67$, $SE = 0.34$, $z = 4.96$) and variable length (RTs: $b = 0.25$, $SE = 0.03$, $t = 7.83$; accuracy: $b = 2.87$; $SE = 0.35$; $z =$ .30) sequences. Importantly, we also observed interaction effects in both measures: the negative impact of length uniformity was significantly greater for grammatically correct sequences (RTs: $b = 0.28$, $SE = 0.04$, $t = 6.24$; accuracy: $b = 3.75$, $SE = 0.46$, $z = 8.15$). Nontransformed data are plotted in Figure 4.

Two aspects of these data warrant extra attention. Firstly, note that "ungrammatical" responses were actually aided by length uniformity (RTs: $b = -0.05$, $SE = 0.02$, $t = -1.87$; accuracy: $b = 1.16$, $SE = 0.43$, $z = 2.69$). This aligns quite well with the idea that length uniformity induces a sense of "unnaturalness" (Cutter et al., 2017, 2018), which would likely be intrinsic to the perception of ungrammaticality too (hence the facilitation). Yet, the vastly stronger impact of length uniformity for grammatical sequences suggests that a mere sense of unnaturalness is not the whole story. We gather that beyond readers' perception of length uniformity per se, it was considerably more difficult to construct a sentence-level representation in the absence of variable word lengths. Indeed, if length uniformity hampered word identification processes in general, rather than the processing of grammar specifically, then similar effects should have been observed for the ungrammatical sequences.

General Discussion

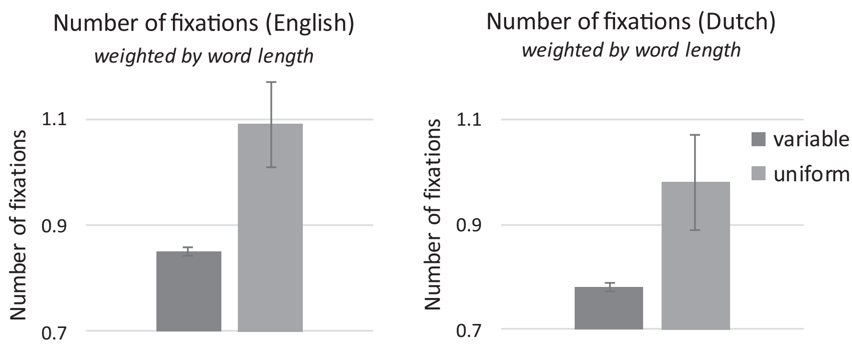
A growing body of research suggests that word position coding is a multifaceted process and that if we are to understand reading in full, we must continue dedicating effort to the inspection and formalization of this novel cognitive construct. OB1-reader (Snell & Grainger, 2019b; Snell, Grainger, & Declerck, 2018) has provided a first step toward this end. A key component of OB1 is the assumption that simultaneously activated lexical representations are matched with candidate locations in a spatiotopic representation, maintained in working memory. Much of the evidence thus far has underpinned the role of top-down (syntactic) constraints herein (e.g., Liu et al., 2020; Mirault et al., 2018; Snell & Grainger, 2019a; Wen et al., 2021). Presently casting a different light on the word position coding process, here we have assembled various bits of evidence indicative of a role for bottom-up visual cues.

Slowed reading upon encountering uniform word length sequences is a straightforward prediction generated by the assumption that activated words are matched with locations on the basis of their length. When an activated word can potentially be matched with multiple locations, or multiple words can be matched with a single location, the brain will have to rely on semantic or syntactic cues to resolve uncertainty, and it is conceivable that such higher-order information is not always as readily available as a simple low-level visual cue such as word length. An analogy may be drawn to the reading of unspaced sentences (*suchasthissequence whichisdecidedlyhardertoread*), the difficulty of which is similarly attributed—among other things—to a lack of word length information to aid sentence recognition (e.g., Mirault et al., 2019; Perea & Acha, 2009). However, a difference between the reading of unspaced sentences and the reading of uniform word length sentences is that word identification per se should not be hampered by length uniformity. Indeed, the reader may, as with any normal sentence, garner the lengths of to-be-recognized words, and use this information to limit the search process (such that "butterfly" does not activate the representations "butter" and "fly"; see, e.g., Snell, Grainger, & Declerck, 2018). The idea that length uniformity cannot obstruct

[8] We also tried a model with random slope for the grammaticality factor, but this model did not converge.

Figure 3

Number of Fixations, Weighted by the Average Word Length



Note. Error bars depict standard errors.

the identification of words all the more compels us to attribute the observed cost in reading to the positioning of words instead.

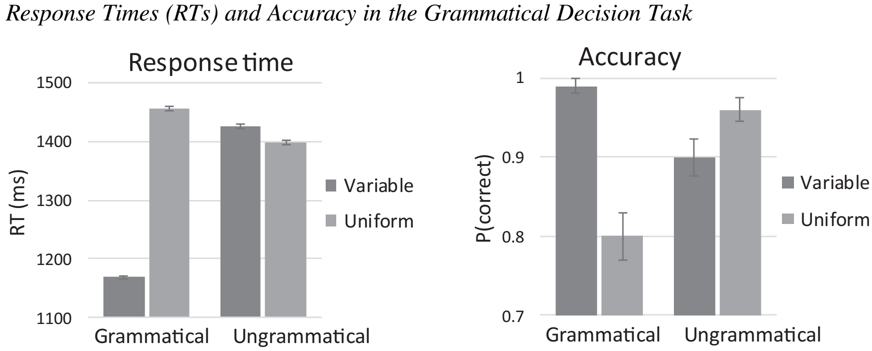
In line with the current results are the important recent findings of Huang and Staub (2021). They replicated the TW effects of Mirault et al. (2018) and, crucially, they found that such TW effects were diminished when the transposed words had different lengths. Huang and Staub noted that this is indeed in line with OB1's assumption that length cues constrain the mapping of activated words onto locations, but at the same time, they argued that a higher error rate for these TW sentences, compared to ungrammatical control sentences, is not in line with OB1's predictions. Here we should point out that the latter claim of Huang and Staub was incorrect. The process of associating words with locations in OB1 is dictated not only by length cues, but also by syntactic constraints. It is precisely for this reason that TW sentences (which can be corrected) are less easily refuted than ungrammatical control sentences (which cannot be corrected)—an effect that is merely amplified when words have equal lengths. Matching words to locations on the basis of word length need not be an all-or-nothing process in OB1; rather, length cues moderately impact certainty about word order.

In addition to the above, we should acknowledge the possibility that there is not always a clear-cut distinction between syntactic cues and length cues, respectively. Short words, for instance, are often articles ("the," and "a"), and might therefore be interpreted as such on the basis of their length rather than orthography. In Dutch reading, we observed a lower number of skips in uniform sentences, which may have been caused by readers' inability to identify (often skipped) article words prior to fixating them. Such effects were not found in English reading, however. Hence, the extent to which length informs syntactic processing (rather than word position coding per se) remains an issue for future inquiry.

One may suspect that the theory set out in this paper does not directly apply to logographic scripts such as Chinese Hanzi or Japanese Kanji, given that these scripts are unspaced, and that the variance in word length is much smaller (i.e., Hanzi and Kanji words are mostly comprised of one or two characters). Important in this respect is the study of Liu et al. (2020), which revealed TW effects in Chinese reading, evidencing that readers of these scripts retain a similar amount of flexibility in word position coding. Crucial with regard to our theory is the fact that one of their experiments (specifically, Experiment 3) yielded TW effects when transposing 3-character words with 1-character words—effects that were equal in magnitude to those obtained with equal-length TWs. In our view, this shows that word position coding in a logographic script is not as strongly guided by low-level visual cues such as word length. OB1 predicts that if one were to add spaces between words (so that, e.g., the TW sequence 他用寻探测器宝 became 他 用 寻 探测器 宝), the sequence would more easily be judged as being incorrect. Indeed, the fact that length uniformity did not modulate TW effects

Figure 4

Response Times (RTs) and Accuracy in the Grammatical Decision Task



Note. Error bars depict standard errors.

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in the study of Liu et al. (2020), we reckon, is precise because length cues are much weaker in unspaced scripts.

More generally, the absence of word length information in logographic scripts does not undermine OB1's assumption that readers use word length cues when these are available. In fact, as reported by Snell, Grainger, and Declerck (2018), early simulations of the model without word length constraints showed that the model *was* able to read—although overall the model performed quite poorly, much akin to the unspaced reading of western alphabetic scripts observed in humans.

In closing, here we have brought together various types of evidence that readers use word length information in the construction of sentence-level representations. As of yet, OB1-reader is the only model that accommodates these behaviors.

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