Development of a Self-paced Sequential Letterstring Reading Task to Capture the Temporal Dynamics of Reading a Natural Language

Ryutaro KASEDO,*, ** Atsuhiko IIJIMA,*, ***, # Kiyoshi NAKAHARA,† Yusuke ADACHI,** Isao HASEGAWA**, $

Abstract  The rhythm of vocalizing a written language depends on a merge process that combines meaningless linguistic units into a meaningful lexical unit, word, or Bunsetsu in Japanese. However, in most previous studies, written language was presented to the participants in lexical units (word-by-word) with explicit inter-word (or inter-Bunsetsu) marks or spacing. Therefore, it has been difficult to conduct psychophysical assessment of the participants’ own speed in segmenting meaningful units from unstructured written language when reading. Here, we hypothesized that the spontaneous reading speed of Japanese readers reflects their own punctuation process, even when sentences are written without punctuation marks or spaces. To test this hypothesis, we developed a new “self-paced sequential letterstring reading task,” which visually presents sentences letter-by-letter. The task required participants to push a button to proceed to the next letter at their own pace, hence allowing evaluation of the reaction time (RT) to individual letters. We found that the average RT decreased parametrically as the position of the letter approached the end of a Bunsetsu. Moreover, the RT increased drastically at the last letter completing the Bunsetsu. Participants were not shown any punctuation marks and not instructed to explicitly recognize the punctuations during reading. Therefore, these effects strongly suggest that the implicit and spontaneous punctuation is the origin of the rhythm in reading. These results show that spontaneous punctuation of letterstring affects the reading speed. The task we have developed is a promising tool for revealing the temporal dynamics of natural reading, which opens a way to shape the fluency of script-to-speech human interfaces.

Keywords: self-paced reading, punctuation, reaction time, temporal dynamics.

Adv Biomed Eng. 10: pp. 26–31, 2021.

1. Introduction

Human-like natural speech has not been reproduced in machines. Vocalization of written sentences requires a merge process [1]. Streams of sublexical constituents or letters are merged into a minimal independent lexical constituent or word (Bunsetsu in Japanese). These minimal lexical constituents are further merged into a higher-order constituent (phrase or sentence). It is therefore reasonable to assume that these hierarchical processes affect the temporal dynamics of speech production. Punctuation helps pronounced syllables to be merged [2–4]. Specifically, syllables are not pronounced at the same tempo but intentionally separated by punctuation with breath, which leads to a characteristic pattern of stressed and unstressed syllables. Moreover, in most written languages, inter-word spaces explicitly emphasize the meaningful units (words), which helps reading. Syntactic processing, such as sequential rules and nesting structure, further assists to merge meaningful units into a higher-order constituent.

Bunsetsu is the minimal independent meaningful
unit in Japanese. Japanese is not usually written with a space between Bunsetsus. Instead, punctuation marks, such as commas and periods, and logographic Chinese characters are used to clarify the border of Bunsetsus in written Japanese. According to previous studies, written Japanese sentences spaced with inter-Bunsetsu spaces were read faster than unspaced sentences [5]. The importance of punctuation in written sentences has been reported in another language [6]. However, in most previous studies, written language was presented to the participants in lexical units (word-by-word) with explicit inter-word (or inter-Bunsetsu) spacing. Therefore, it has been difficult to conduct psychophysical assessment of the participants’ own rhythm to segment meaningful units from unstructured written language when reading. Here, we hypothesized that Japanese readers segment Bunsetsu units by themselves, even when written sentences are presented without punctuation marks or spaces, and that their spontaneous reading speed reflects their own punctuation process. To test this hypothesis, we developed a new “self-paced sequential letterstring reading task,” which presented Japanese sentences letter-by-letter without punctuation marks. The task required the subject to push a button to proceed to the next letter at their own pace. Since the task allowed evaluation of the reaction time (RT) letter-by-letter, the importance of punctuation in spontaneous reading speed could be directly verified. By assessing the participants’ own reading speed, the participants’ spontaneous reading rhythm depending on the position of Bunsetsu end could be detected. The rhythm detection would have two implications. First, from an engineering point of view, it would provide a key to developing new human machine interfaces vocalizing human-like natural speech from written languages. Second, from a neurolinguistic point of view, the discovery of the participants’ own rhythm in segmenting meaningful units would lead to better modeling of hemodynamic neural changes time-locked to linguistic ‘merge’ processes, which construct a new linguistic constituent from lower-level constituents.

2. Materials and Methods

2.1 Participants

Thirty-four Japanese speakers (male/female: 20/14, age: 18–22 years, right-handed, no history of neuropa-thy) participated in the experiment, which was approved by the ethical committees at the Niigata University (2015-3020) and Kochi University of Technology (58C-4). Participants provided written informed consent and received 1000 yen per hour for participation. One participant was excluded from the analysis because he slept during the experiment. Another participant was excluded because a different stimulus set was used for this partici-pant.

2.2 Stimuli and behavioral task

The participants performed the “self-paced sequential letterstring reading task,” as shown in Fig. 1A. The stimuli were “Kana” letters (Fig. 1B, C), syllabaries that are part of the Japanese writing system, and an asterisk. We collected simple sentences from ‘Aozora-Bunko’ (https://www.aozora.gr.jp/), which is a digital library publishing text data with no copyrights, and presented them in a random order. The sentences were independent of each other, because any semantic link between sentences should have an effect on reading speed. In the task, a string of Kana letters was sequentially presented one-by-one. Specifically, following presentation of a letter, the participant was required to push a button to proceed to the next letter, so that they read the temporal string of letters at their own pace. The RT in response to each letter was measured, as shown in Fig. 1D. The next stimulus was presented 50 ms after the participant pushed the button. In the “meaningful letterstring presentation period” or main task period of the experimental run, ten sentences were presented without any punctuation mark (Fig. 1B, C). Each sentence was a simple one with only one set of subject and predicate. Before and after the main task period, a meaningless random letter-string, which did not construct any linguistic phrase or sentence, was presented. Asterisks were presented twice, once to indicate the start and once to indicate the end of the main task period (Fig. 1A). We projected the visual stimuli at 1.1 degrees of visual angle on a display. (PROPixx, VPixx Technologies Inc). The timing of visual stimulation and RT measurement were controlled by the Presentation software (Neurobehavioral systems, Berkeley, CA, USA) installed on a personal computer.

2.3 Experimental protocols

Initially, we gave three instructions to the participants:

(1) Japanese sentences will appear letter by letter as you push a button.

(2) Read the sentences silently. Push the button at your own pace to follow their meanings.

(3) Stimuli are only simple sentences comprising ‘Kana’ letters. No punctuation marks are included. Indi-vidual sentences are independent from one another.

Then, prior to the psychophysical test of 6 runs, the participants conducted a pre-training run with a stimulus set not used in the test. The aim of this pre-training was familiarization to the experimental setup, devise opera-tion, and the task sequence. Participants performed six runs of the “self-paced sequential letterstring reading task” (Fig. 1A) following the pre-training. At the begin-ning of each run, 20 random letters were sequentially
presented (Fig. 1A). Subsequently, an asterisk was presented to indicate the start of the main task period, during which 175 letters constituting ten meaningful sentences were sequentially presented without punctuation marks. At the end of the main task period, another asterisk was presented, followed by a string of twenty random letters.

2.4 Behavior analysis
We classified each letter in the meaningful letterstring according to its position relative to the Bunsetsu end. Specifically, we assigned position "0" to the letter at the Bunsetsu end, position "−1" to the first letter before the Bunsetsu end, and so on. We normalized the RT by the average RT for each Bunsetsu per participant as:
\[ RT'_n = \frac{RT_n}{RT_{\text{average}}} \]  

(1)

\(RT_n\) is the RT for the letter at the \(n\)-th position relative to \((n\)-letters before\) the Bunsetsu end. \(RT_{\text{average}}\) is the average RT per participant for all letters constituting a particular Bunsetsu. We evaluated Pearson’s correlation coefficient between the \(RT'_n\) averaged across participants and the position relative to the Bunsetsu end. We rejected those runs in which an RT of over 5000 ms was measured during the main task period. MATLAB (MathWorks, Natick, MA) was used for data analysis.

3. Results

3.1 Change in RT with the letter position relative to the Bunsetsu end

The average RT for the letters at the same relative position within the Bunsetsu are shown in Fig. 2. The RT decreased gradually as the position of the letter approached the Bunsetsu end. The RT for the final letter of the Bunsetsu (position “0”) higher than that for the letter presented just before the Bunsetsu end (position “−1”). Friedman’s test showed a statistically significant difference of the average RT depending on the letter position in the Bunsetsu \((F(7, 32) = 6.81 \times 10^5, P = 3.52 \times 10^{-12})\).

3.2 Effect of the letter position relative to the Bunsetsu end on the RT

To statistically test the relationship between the RT and the letter position relative to the Bunsetsu end, we initially evaluated the correlation coefficient (see 2.4).

3.3 The effect of Bunsetsu end

Finally, we tested whether the normalized RT (Eq. (1)) for the last letter closing a Bunsetsu (position “0”) was significantly higher than the normalized RT for the letter immediately before (position “−1”). We found that the normalized RT increased significantly \((P = 1.16 \times 10^{-6}, \text{Wilcoxon signed-rank test})\) at the Bunsetsu end (Fig. 4).

---

As shown in Fig. 3, we found that the normalized RT (Eq. (1)) decreased parametrically as the letter approached the Bunsetsu end (Pearson’s correlation coefficient: \(-0.451, P = 1.28 \times 10^{-12}\)).

**Fig. 2** Change in the average RT according to the letter position in the Bunsetsu.

We averaged the RT for the letters at the same relative position across different Bunsetsus for each of the 32 participants. Blue circle: average RT across all 32 participants. Error bar: standard error of the mean \((n = 32)\).

**Fig. 3** RT decreases towards the Bunsetsu end.

We tested the relationship between the RT and letter position relative to the Bunsetsu end. Blue circle: average-normalized RT of each participant \((n = 32)\).

**Fig. 4** Increased RT at the Bunsetsu end.

We tested whether the RT to the letter at the Bunsetsu end (position “0”) was significantly higher than that to the letter before (position “−1”). Blue circle: average-normalized RT of each participant \((n = 32)\). Red cross: average-normalized RT across all participants \((n = 32)\).
4. Discussion and Conclusion

In the present study, the participants were not instructed to explicitly attend to punctuation while reading unpunctuated and unspaced written letterstrings. Nonetheless, the RT parametrically decreased as the position of the presented letter approached the Bunsetsu end (Fig. 3) and drastically increased when the last letter completing the Bunsetsu was presented (Fig. 4). These results suggest that natural reading has an intrinsic rhythm: the speed gradually accelerates approaching the Bunsetsu end and then pauses after the Bunsetsu end, even when no external punctuation cues are provided. The gradual acceleration of the speed is reasonable because the process of prospective anticipation of the upcoming letter may become faster as the whole picture of the Bunsetsu becomes clearer. Earlier neurophysiological studies showed that transient brain activations correlated with the number of nodes when these nodes were closed [7]. The sudden rise in RT at the Bunsetsu end, which is presumably equivalent to the breath in speech, could be ascribed to some linguistic load or process required for closing a meaningful unit. In this respect, our findings are consistent with those of a previous study indicating that Japanese sentences broken down into Bunsetsus were read faster than unbroken ones [8].

We presented Kana letters to the participants in this experiment. Kana letters are the minimal units of spoken language, as well as written language in Japanese. Therefore, the temporal dynamics of the RT evaluated in this experiment should have fundamental importance, not only in written language but also in spoken language.

Our results provide direct evidence demonstrating an important effect of grouping a minimal meaningful unit, such as a Bunsetsu from sublexical letterstring, on reading a natural language. Generation of meaningful units from unstructured letterstring accompanies spontaneous regular rhythm in reading. This effect may be a major factor accounting for the previous finding that prosodic phrasing [9] or rhythm [10, 11] has an influence on speech comprehension.

Several important factors might have potentially influenced participants’ spontaneous reading rhythm. First, “morphological analysis” is very important for natural language process. Morphological awareness affects the reading process and reading-related neural activity [12, 13]. Second, use of complex sentences that can be interpreted into multiple meanings is essential to approach the accurate mechanism of human language recognition. Actually, in a spoken language [14] and a written language [7], neural activations related to hierarchal structuring were reported. Furthermore, increase of neural activity with the number of merged nodes was also reported [15]. Although the scope of the present study is to clarify how reader’s spontaneous reading rhythm depends on the position of the letter within Bunsetsu, it should be important to examine the effects of those between-Bunsetsu factors that may potentially affect the reader’s spontaneous rhythm in the future.

Today, many linguistic assist devices that automatically translate written scripts into speech or braille have been developed. However, optimization of the rhythm of speech reproduction or braille motion is still far from complete compared to that of natural human speech. The novel “self-paced sequential letterstring reading task” we have developed in the present study is a promising tool for revealing the temporal dynamics of natural reading, which opens a way to shape the fluency of such script-to-speech and/or script-to-braille interfaces.

Acknowledgement

This work was supported in part by Grants KAKENHI 23300150, 26242088, and 19H01038 from MEXT, Japan to I.H.

Conflict of Interest

We have no conflict of interest with any company or commercial organization.

References

1. Friederici AD, Chomsky N, Berwick RC, Moro A, Bolhuis JJ: Language, mind and brain. Nature Human Behav. 1(10), 713–722, 2017.

2. Fotidzis TS, Moon H, Steele JR, Magne CL: Cross-modal priming effect of rhythm on visual word recognition and its relationships to music aptitude and reading achievement. Brain Sci. 8(12), 210, 2018.

3. Cason N, Schön D: Rhythmic priming enhances the phonological processing of speech. Neuropsychologia. 50(11), 2652–2658, 2012.

4. Zhang N, Zhang Q: Rhythmic pattern facilitates speech production: An ERP study. Sci Rep. 9(1), 12974, 2019.

5. Matsuda M: The influence of space information on reading of Japanese sentences. Jpn J Psychonomic Sci. 19(2), 83–92, 2001.

6. Chafe W: Punctuation and the prosody of written language. Written Commun. 5(4), 395–426, 1998.

7. Nelson MJ, El Karoui I, Giber K, Yang X, Cohen L, Koopman H, Cash SS, Naccache L, Hale JT, Pallier C, Dehaene S: Neuropsychological dynamics of phrase-structure building during sentence processing. Proc Natl Acad Sci U S A. 114(18), E3669–E3678, 2017.

8. Kobayashi, J, Sekiguchi, T, Shinbori, E, Kawashima T: Readability of Japanese electronic text with Bunsetsu-based layouts. Trans Jpn Soc Artif Intell. 32(2), A-A130_1-24, 2017.

9. Frazier L, Carlson K, Clifton C Jr: Prosodic phrasing is central to language comprehension. Trends Cognitive Sci. 10(6), 244–249, 2006.

10. Roncaglia-Denissen MP, Schmidt-Kassow M, Kotz SA: Speech
rhythm facilitates syntactic ambiguity resolution: ERP evidence. PLoS One. 8(2), e56000, 2013.

11. Magne C, Astésano C, Aramaki M, Ystad S, Kronland-Martinet R, Besson M: Influence of syllabic lengthening on semantic processing in spoken French: behavioral and electrophysiological evidence. Cerebral Cortex. 17(11), 2659–2668, 2007.

12. Levesque KC, Kieffer MJ, Deacon SH: Morphological awareness and reading comprehension: Examining mediating factors. J Exp Child Psychol. 160, 1–20, 2017.

13. Koester D, Schiller NO: Morphological priming in overt language production: electrophysiological evidence from Dutch. Neuroimage. 42(4), 1622–1630, 2008.

14. Ding N, Melloni L, Zhang H, Tian X, Poeppel D: Cortical tracking of hierarchical linguistic structures in connected speech. Nat Neurosci. 19(1), 158–164, 2016.

15. Pallier C, Devauchelle AD, Dehaene S: Cortical representation of the constituent structure of sentences. Proc Natl Acad Sci U S A. 108(6), 2522–2527, 2011.

Ryutaro KASEDO

Ryutaro KASEDO received the BS degree in Engineering from Department of Biocybernetics, Faculty of Engineering, Niigata University in 2019. He is a master course student in Graduate school of Science and Technology, Niigata University. His research interests include cerebral physiology by neuroimaging and biomedical engineering. He is a member of The Japan Neuroscience Society.

Atsuhiko IIJIMA

Atsuhiko IIJIMA received the BS, MS, and PhD degrees in Biomedical Engineering from Keio University in 1999, 2001, and 2003, respectively. He was a Research Fellow for the Young Scientists of the Japan Society for the Promotion of Science (2002–2004). He was an Assistant Professor in the Department of Physiology, Niigata University School of Medicine (2004–2010), an Assistant Professor (2010–2013), and an Associate Professor (2013–2018) in the Department of Biocybernetics, Faculty of Engineering, Niigata University. He is currently an Assistant Professor in the Department of Health Sciences, Faculty of Medicine and the Department of Interdisciplinary Program of Biomedical Engineering, Assistive Technology, and Art and Sports Sciences, Faculty of Engineering, Niigata University. His research interests include neurophysiology and biomedical engineering in visual neurosciences.

Yusuke ADACHI

Yusuke ADACHI received the Ph.D. degree from Department of Physics, Graduate School of Science, the University of Tokyo. He was an Assistant Professor in the Department of Physiology, the University of Tokyo School of Medicine and is currently an Assistant Professor in the Department of Physiology, Niigata University School of Medicine. His research interests include neurophysiology, neuroimaging, and behavioral analysis of cortical functions in humans and nonhuman primates.

Kiyoshi NAKAHARA

Kiyoshi NAKAHARA received the BS degree in Engineering from Department of Biocybernetics, Faculty of Engineering, Niigata University in 2019. He is a master course student in Graduate school of Science and Technology, Niigata University. His research interests include cerebral physiology by neuroimaging and biomedical engineering. He is a member of The Japan Neuroscience Society.