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Title	Early stages of visual word processing in Japanese Hiragana : Psychophysiological correlates of expertise in reading
Author(s)	奥村, 安寿子
Degree Grantor	北海道大学
Degree Name	博士(教育学)
Dissertation Number	甲第11856号
Issue Date	2015-03-25
DOI	https://doi.org/10.14943/doctoral.k11856
Doc URL	https://hdl.handle.net/2115/59178
Type	doctoral thesis
File Information	Yasuko_Okumura.pdf



北海道大学 大学院教育学院
博士学位論文

**Early Stages of Visual Word Processing in Japanese Hiragana:
Psychophysiological Correlates of Expertise in Reading**

奥村安寿子

Table of Contents

Abstract	iv
List of Figures	viii
List of Tables.....	viii
1. Introduction	1
1.1. What is Reading?	1
1.2. Acquisition of Reading	3
1.3. Measures of Visual Word Processing	5
<i>1.3.1. Behavioral measures</i>	<i>5</i>
<i>1.3.2. Event-related potentials.....</i>	<i>5</i>
1.4. Reading-related Expertise in Early Stages of Print Processing	6
<i>1.4.1. Perceptual categorization of print stimuli.....</i>	<i>6</i>
<i>1.4.2. Early phonological mapping</i>	<i>7</i>
<i>1.4.3. Perceptual integration of letters into letter strings</i>	<i>9</i>
1.5. Print-tuned N170 Component of Event-Related Potentials.....	12
<i>1.5.1. Overview of N170.....</i>	<i>12</i>
<i>1.5.2. Reading-related specialization of N170 and its neural substrate</i>	<i>12</i>
<i>1.5.3. Print-tuned N170 as an index of reading-related expertise</i>	<i>13</i>
1.6. Purpose of the Study.....	16
<i>1.6.1. Early print processing under rapid stimulus presentation.....</i>	<i>16</i>
<i>1.6.2. Early stages of Hiragana string processing and print-tuned N170</i>	<i>16</i>
<i>1.6.3. Overview of the study</i>	<i>17</i>
2. Experiment 1.....	19
Fast Perceptual Categorization of Hiragana Strings under Restriction of Attention	19
2.1. Introduction	19
2.2. Methods	21

2.2.1. <i>Participants</i>	21
2.2.2. <i>Stimuli</i>	21
2.2.3. <i>Procedure</i>	23
2.2.4. <i>Recordings and analysis</i>	23
2.3. Results	24
2.3.1. <i>Target detection</i>	24
2.3.2. <i>Event-related potential data</i>	24
2.4. Discussion	27
2.5. Conclusion	28
3. Experiment 2	29
Role of Visual Attention in Early Phonological Mapping	29
3.1. Introduction	29
3.2. Methods	33
3.2.1. <i>Participants</i>	33
3.2.2. <i>Stimuli</i>	34
3.2.3. <i>Procedure</i>	35
3.2.4. <i>Recordings and analysis</i>	36
3.3. Results	38
3.3.1. <i>Target detection</i>	38
3.3.2. <i>ERP data</i>	39
3.4. Discussion	42
3.4.1. <i>Attention is involved in N170 left-lateralization</i>	43
3.4.2. <i>The earliest specialization for words</i>	45
3.5. Conclusion	47
4. Experiment 3	48
Unit of Print Representation in Fast Perceptual Categorization	48
4.1. Introduction	48
4.2. Methods	51

4.2.1. <i>Participants</i>	51
4.2.2. <i>Stimuli</i>	51
4.2.3. <i>Procedure</i>	52
4.2.4. <i>Recordings and analysis</i>	54
4.3. Results	56
4.3.1. <i>Behavioral Results</i>	56
4.3.2. <i>ERP data for standard stimuli</i>	58
4.4. Discussion	63
4.4.1. <i>Perceptual units for the bilateral print-tuned N170</i>	63
4.4.2. <i>Integration of character strings and behavioral outputs</i>	66
4.5. Conclusion	67
5. General Discussion	68
5.1. Summary of the Experimental Findings	68
5.2. Hiragana String Processing under Rapid Stimulus Presentation	70
5.2.1. <i>Early perceptual processing of Hiragana letters</i>	70
5.2.2. <i>Rapid Neural Specialization for Hiragana Words</i>	72
5.2.3. <i>Early phonological mapping</i>	74
5.3. Early Stages of Hiragana String Processing: Overview and Model	75
5.4. Issues for Future Research	77
5.4.1. <i>Cross-linguistic comparisons</i>	77
5.4.2. <i>Course of development</i>	79
5.5. Implications for Developmental Dyslexia	80
5.5.1. <i>Examining orthographic processes via bilateral print-tuned ERP</i>	81
5.5.2. <i>Visual attention deficits may impede access to phonology</i>	82
5.5.3. <i>Connections with the visual attention span deficit hypothesis</i>	83
5.6. Concluding Remarks	85
6. References	86

Abstract

Reading is the act of deciphering strings of symbols to obtain the information they represent. It is central to our learning, daily life, and culture. Children learn to read early in school, and years of practice and experience make it possible to read words and text with remarkable fluency. However, some children and adults show difficulties in learning to read despite normal intelligence and an adequate educational environment. Therefore, it is important to disentangle the act of reading not only to know its underlying mechanisms, but also to promote literacy. The present study aimed to examine the psychophysiological correlates of fluent reading of Hiragana in expert adult Japanese readers at the level of a single word/letter string.

As readers become more experienced in reading, their speed and efficiency in various aspects of print processing increase greatly. Particularly, experience-dependent changes in early processes appear to be important. Therefore, the present study focused on three processes that have been considered to exist in the early stages of expert print processing; i.e., fast perceptual categorization, early phonological mapping, and the perceptual integration of letters into a letter string. Fast perceptual categorization is the process of classifying visual inputs of print as those representing letter/character strings and to differentiate them from other visual stimuli. This process should contribute to the rapid induction of subsequent phonological and/or semantic processes. Early phonological mapping refers to the activation of phonological information that occurs obligatorily and rapidly after the presentation of print. This indicates that phonology plays an integral role in expert reading. The perceptual integration of letters is the

process of grouping the constituents of letter/character strings into unified percepts, which should enable efficient whole-word reading.

These processes are completed within an extremely short amount of time after visual contact with print. Therefore, the present study used the event-related brain potential (ERP) as a primary index. The ERP has an exquisite temporal resolution, which provides the opportunity to examine the precise time course of brain activities while participants are engaged in stimulus processing. Previous ERP studies of print processing have identified a left occipito-temporal N170 component that is specifically enhanced in response to print stimuli and which has been shown to be related to the three processes mentioned above. In previous studies, however, the print-tuned N170 was examined by using low stimulus presentation rates, which is clearly in contrast to normal reading, which involves rapid print input. Therefore, the present study examined early print processing reflected in the print-tuned N170 under rapid stimulus presentation to resemble normal reading. Moreover, while N170 has been well-studied with alphabetic scripts and increasingly with Chinese logographic kanji, only a few studies have considered Hiragana script. Hiragana is distinct from other scripts due to its extremely transparent letter-to-sound mapping, but early processes with this script have not been studied intensively. Thus, the present study examined the early stages of Hiragana string processing in expert adult Japanese readers by using rapid stimulus presentation and ERPs

Experiment 1 examined whether an early print-tuned ERP response can be observed when linguistic processing is highly restricted. While presented with a rapid

stimulus sequence consisting of Hiragana words, nonwords, and symbols, participants detected changes in the color of a fixation cross, which made Hiragana and symbol strings completely task-irrelevant. As a result, occipito-temporal N1 in response to Hiragana strings was enhanced compared to that for symbols. Therefore, Experiment 1 showed that fast perceptual categorization operates largely independent of linguistic processing. However, the result of Experiment 1 lacked characteristic left-lateralization of the print-tuned N170, which raised the possibility that rapid stimulus presentation and/or the fact that the task required the participants to ignore Hiragana strings may have affected some aspect of early print processing.

Experiment 2 examined the possibility that automatic phonological mapping processes, which are considered to be reflected in N170 left-lateralization, require attention to print stimuli. With the same stimulus sequence as in Experiment 1, this experiment required participants to discriminate the color of stimuli, instead of fixation. As a result, Hiragana words and nonwords elicited left-lateralized N170, but only when constituent letters were located close together. This result, when compared to that of Experiment 1, indicated that early phonological mapping processes in Hiragana script require attention to the print itself.

Experiment 3 examined whether the bilateral print-tuned N170 identified in Experiments 1 and 2 involved representations of separate letters or integrated letter strings. To this end, Experiment 3 examined lateralized spatial attention effects in early visual ERPs as an index of perceptual integration. As a result, an N1 attention effect was observed equally for print and symbol stimuli, which suggested that the bilateral

N170 specialization for Hiragana strings occurs based on the representation of separate letters. On the other hand, bilateral N170 specialization emerged earlier than the N1 attention effect, which suggested that individual Hiragana letters may have unified representation irrespective of attentional processes associated with the N1 attention effect.

The results of these three experiments suggested that early stages in Hiragana string processing involve multiple neural processes that are specialized for letters and/or letter strings, in the case of expert adult readers. Among them, the detection of letters and fast perceptual categorization were shown to occur even when attention to print stimuli is highly restricted. In contrast, while specialized processes for early phonological mapping and the early integration of letter strings have been shown to exist, the results suggested that their implementation required spatial attention to an entire letter string. These findings lead to the novel notion that visual attention plays a critical role in expert print processing, opposed to the general view that it operates automatically upon visual contact with print. Since visual attention deficits have been considered to cause developmental dyslexia, the findings in the present study should help us to understand not only the mechanisms of fluent reading in experts but also those of impaired reading.

List of Figures

Figure 1-1. Overview of visual word processing.	2
Figure 1-2. The Interactive Activation Model.	10
Figure 1-3. Neurobiological scheme of visual word recognition.	11
Figure 2-1. Stimuli and experimental procedure in Experiment 1.	22
Figure 2-2. ERP results of Experiment 1.	26
Figure 3-1. Stimuli and experimental procedures in Experiment 2.	34
Figure 3-2. ERP results during 70-100 ms poststimulus (Oz) in Experiment 2.	40
Figure 3-3. ERP results during 130-170 ms poststimulus (P7, P8) in Experiment 2.	41
Figure 4-1. Stimuli and experimental procedures in Experiment 3.	53
Figure 4-2. Behavioral results of Experiment 3.	57
Figure 4-3. Grand-average ERPs in Experiment 3.	60
Figure 4-4. Topographic distributions of attention effects and stimulus effects during P1, early N1, and late N1 latency ranges in Experiment 3.	61
Figure 4-5. Mean amplitudes of ERPs for standard stimuli during P1, early N1, and late N1 latency ranges in Experiment 3.	62
Figure 5-1. Time course and involvement of attention in early processes related to print-tuned N170 in response to Hiragana strings.	69
Figure 5-2. A putative model of early Hiragana string processing.	77

List of Tables

Table 3-1. Behavioral results of Experiment 2.	38
Table 4-1. Summary of statistical results for ERPs in the Experiment 3.	58

1. Introduction

1.1. What is Reading?

The use of letters to record and propagate words started approximately 5500 years ago. Reading emerged as a consequence of this invention. For a long time, only a small portion of people could actually read. However, the invention of typography and an increase in formal education have made reading an ordinary skill that anyone can learn, although literacy is still not universal. Nowadays, reading is central to our learning, daily life, culture, and communication. On the other hand, some people have difficulties in reading. For example, people with developmental dyslexia exhibit specific difficulties in learning to read, despite normal intellectual abilities, an adequate educational environment, and sufficient motivation. Therefore, it is important to disentangle the act of reading not only to know its underlying mechanisms, but also to promote literacy.

Reading is basically the act of deciphering strings of symbols to gain access to their pronunciation and/or the meanings they represent. Achieving this goal requires a series of complex perceptual and cognitive operations, as illustrated in a comprehensive model of visual word recognition (Figure 1-1: Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). When a visual word is projected onto the retina, it is split into myriad fragments by retinal neurons (Dehaene, 2009). At the level of initial visual cortical processing, signals from the retinal neurons are converted to represent simple visual features, such as lines and curves. The first major task for readers is to put those fragmented pieces back together to identify what letters are present, the order in which

the letters appear, and the word they comprise. These roughly correspond to the visual feature units, letter units, and orthographic input lexicon in Figure 1-1. Subsequently, access to sounds represented by letters and words (i.e., phonology) may take place. This is done either by matching the identified word to its spoken form (i.e., phonological output lexicon) or by the rule-based conversion of letters into sound (i.e., grapheme-phoneme rule system). Access to meaning is achieved via a semantic system, and finally the reader can read the word aloud or comprehend its contents.

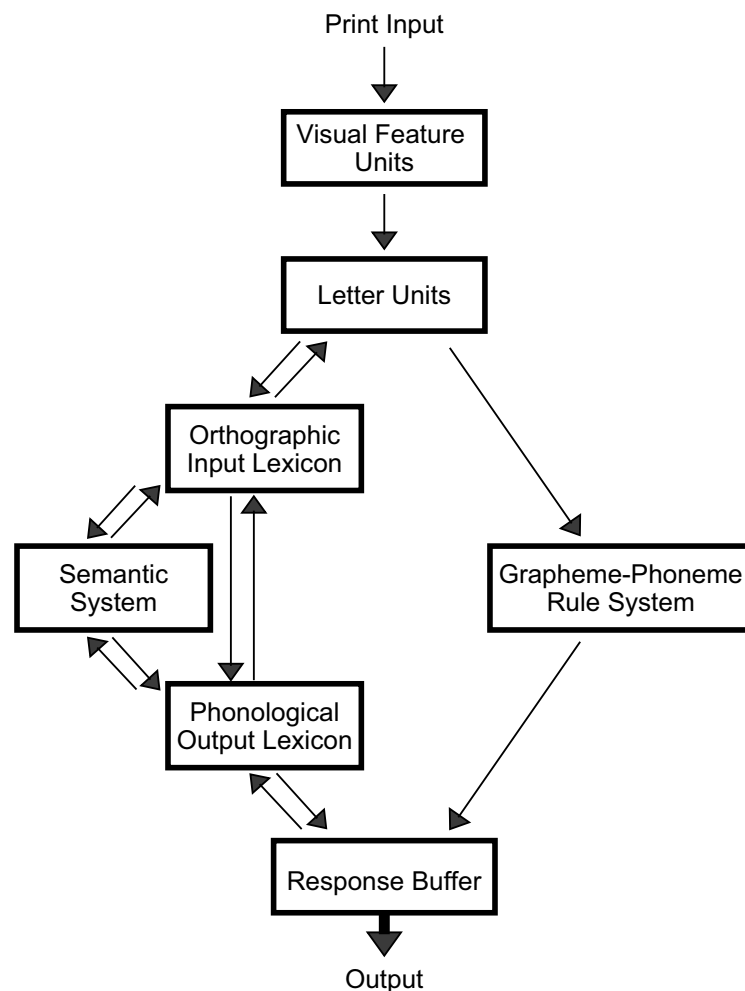


Figure 1-1. Overview of visual word processing.

Adopted and modified from the Dual Route Cascaded Model of Visual Word Recognition in Coltheart et al., 2001.

One way to approach the mechanisms of reading would be to clarify how these operations are accomplished in the course of visual word processing. Therefore, the present study focused on reading at the level of a single word.

1.2. Acquisition of Reading

A marked feature of reading is its potential speed and efficiency. When reading a text for comprehension, fast adult readers can read as many as 500 words per minute, which represents approximately 120 milliseconds per word (Jackson & McClelland, 1975). In experimental settings, competent readers can make judgments regarding the higher-order properties of words (e.g., phonology and semantics) within several hundred milliseconds, including the times required for the preparation and execution of motor responses. These findings show that the operations in visual word processing described above are completed almost instantly upon visual contact with a word.

However, reading in young children is nothing like that. Many children initially struggle with reading, and decipher words slowly with considerable effort. At the very beginning of reading acquisition, children read words in a way described as “logographic” or “pictorial” (Frith, 1985). They rely on any available visual features, such as the shape, color, orientation of line segments, and curvature, to recognize words, as though they were recognizing objects. Although children manage to learn some words through logographic reading, such an understanding is often erroneous and unstable; e.g., they may read *smaller* as *yellow*, since they share a similar visual feature (i.e., two vertical lines in a row). In the next stage, called the “alphabetic stage” (Frith,

1985), children learn how letters correspond to phonology, and gain sound-mediated access to a word's meaning. To achieve this goal, children decipher words letter by letter, which is reflected by a longer processing time for words that consist of more letters (i.e., word length effect, Martens & de Jong, 2006; Zoccolotti et al., 2005). These behavioral phenomena suggest that reading in children requires that considerable attention be deployed on various visual features and/or individual letters in words.

Years of hard practice and experience can dramatically improve the efficiency of reading. Skilled adult readers seem to no longer deploy attention to each letter, as evidenced by disappearance of the word length effect (e.g, Frederiksen & Kroll, 1976). Instead, they are able to read words with an extremely limited deployment of attention to each letter or word, considering the rate at which they can process words (Jackson & McClelland, 1975). A key to such a change is automatization. Just as with activities in daily life and sports, extensive practice in reading seems to automatize the operations in visual word processing, so that it becomes less attention-demanding. In other words, skilled reading may be associated with “expertise,” the concept and manifestation of which has been a recent focus of interest in visual information processing, including of words (Palmeri, Wong, & Gauthier, 2004). Therefore, clarification of the mechanisms that underlie visual word processing from the perspective of reading-related expertise should help us to better understand how fast and efficient reading is realized.

1.3. Measures of Visual Word Processing

1.3.1. *Behavioral measures*

Visual word processing studies have established several sophisticated experimental paradigms to examine its various aspects through the use of behavioral indices, such as reaction time and accuracy. They typically use a task that requires access to a specific aspect of words (e.g., semantic judgment) in combination with the manipulation of psycholinguistic parameters, such as frequency, lexicality, and orthographic and/or phonological regularity. Importantly, behavioral studies have also developed ways to examine automatic processes, which are defined as those that occur despite the absence of task demand (e.g., phonological processing during semantic judgment). For example, in the priming paradigm, the properties of task-irrelevant prime words may facilitate or inhibit responses to target words, which is regarded as evidence of automatic processing. While these methodologies have contributed greatly to the clarification of visual word processing, they are not suitable for precisely examining its time course, since behavioral indices are the final output of multiple stages of processing.

1.3.2. *Event-related potentials*

Event-related potentials (ERPs) index electrophysiological brain activities that are time-locked to a particular sensory, motor or cognitive event. ERPs are extracted from scalp-recorded electroencephalography (EEG) by averaging many time-locked epochs to suppress background EEG activities that are unrelated to the event of interest. Since average ERPs are most likely to reflect the sum of post-synaptic potential activities in the neocortex, they can provide a good estimate of neural processes that are associated with analysis of an event.

ERPs have an exquisite temporal resolution that spans from milliseconds to seconds, and thus they provide precise information on the time course of event processing. Moreover, many studies have linked various psychological processes to specific ERP components, which are defined by their polarity, latency, scalp distribution, and responsiveness to specific psychological manipulations. Visual word processing consists of a series of mental operations that are completed within several hundred milliseconds. Therefore, ERPs are a useful tool for measuring specific operations and tracing the course of visual word processing, especially those that occur immediately after visual contact with words. Therefore, the present study used ERPs as a primary measure, along with behavioral measures when necessary.

1.4. Reading-related Expertise in Early Stages of Print Processing

While experience-dependent changes occur in various aspects of print¹ processing, changes in early stages are particularly important. Among them, the present study focused on three processes that may be closely associated with expertise in reading.

1.4.1. Perceptual categorization of print stimuli

The first process is called fast perceptual categorization, which is the classification of visual words and word-like stimuli as representing print. This process has been evidenced by neural responses that are enhanced for print compared to other visual objects. For example, Nobre, Allison, & McCarthy (1994) found enlarged N200 in

¹ Hereafter, the following terms will be used in the sense defined below. “Letter”: linguistic symbols of phonetic scripts (e.g., alphabets and Hiragana). “Character”: linguistic symbols of logographic scripts (e.g., kanji). “Print”: written language in any form, including single letters/characters, letter strings, and character strings.

response to letter strings relative to that in response to pictures of objects in intracranially recorded ERPs at the posterior fusiform regions. Importantly, the sensitivity to letter strings was not modulated by lexicality, word class, or the context in which words were presented. A similar response was also found in scalp-recorded ERPs within 200 after stimulus presentation (Schendan, Ganis, & Kutas, 1998). Functional neuroimaging studies have linked such categorization processes to a cluster of the left occipito-temporal region called the Visual Word Form Area (VWFA), as evidenced by increased activation of that area in response to visual words relative to the response to pictures (e.g., Szwed et al., 2011). These empirical findings indicate the existence of the rapid visual analysis of letter strings in expert reading, which should be beneficial for the efficient induction of subsequent phonological and/or semantic processes.

1.4.2. Early phonological mapping

Although the primary purpose of reading is to comprehend the meaning of written words, one necessary prerequisite to achieve this goal is to gain access to their sounds. Learning to read begins with knowing how to match letters/characters, or words, to distinctive units of sounds (i.e., phonology), which is typically mastered through making extensive practice of reading aloud. This process is called phonological mapping, and its mastery allows children to link print to the vocabulary in their spoken lexicon that is associated with meaning. Acquisition of a system for phonological mapping also enables children to sound out novel words, which is particularly important for learning new words. As children gain experience with reading, the efficiency of phonological mapping improves greatly, which is indicated by an increase in the speed

of reading aloud.

In expert adult readers, the role of phonology in reading may not seem as explicit as that in children, as evidenced by silent reading. However, numerous studies on visual word processing have demonstrated that expert reading involves phonological mapping obligatorily and rapidly after visual contact with print. As behavioral evidence, Van Orden (1987) showed that, in a semantic categorization task (e.g., FLOWER or not), participants erroneously accept words (e.g., ROWS) and pseudowords (e.g., ROZE) that share the same phonology with the true member of a category (e.g., ROSE). These results indicate that the generation of phonology from letter strings occurs and influences a task even when explicit pronunciation is not required.

Further support for the above notion comes from masked phonological priming studies, in which the combination of a very short stimulus duration (i.e., typically < 50 ms) and a masking procedure limits the exposure to primes (for a review, see Rastle & Brysbaert, 2006). By using this paradigm, Grainger & Ferrand (1994, 1996) revealed that brief exposure to a phonologically-identical pseudoword prime (e.g., roze) facilitates the lexical decision of a target (e.g., ROSE), compared to an orthographically related prime (e.g., rove). Since primes were presented so quickly that participants were not even consciously aware of them, the masked priming effect strongly supports early phonological mapping that arises immediately after print input. The earliness of phonological mapping was further confirmed by measurements of ERPs elicited by targets in the same paradigm, in which the effect of the phonological congruency between primes and targets was found at around 250 ms poststimulus in one study

(Grainger, Kiyonaga, & Holcomb, 2006) and as early as 100 ms in other studies (Ashby, Sanders, & Kingston, 2009; Ashby, 2010).

Converging evidence for the obligatory and rapid involvement of phonological mapping in print processing suggests that phonology has an integral role in expert reading (for reviews, see Frost, 1998; Halderman, Ashby, & Perfetti, 2012). It also suggests that early phonological mapping may facilitate accurate and fluent reading by skilled adult readers.

1.4.3. Perceptual integration of letters into letter strings

In visual word processing, print inputs are initially represented as fragmented pieces of visual features (Dehaene, 2009). Therefore, their rapid integration into meaningful units, such as letters/characters and whole words, must be crucial for efficient reading. A conceptual schema of this process is illustrated in Figure 1-2 (McClelland & Rumelhart, 1981), which starts out with the detection of basic visual features such as line segments with different orientations. The features activate letters that contain them, and in turn connect to words that consist of the activated letters. In neurobiological terms, such integration is achieved through a hierarchy of visual neurons that are tuned to different constituent units of letter strings. As illustrated in Figure 1-3 (Dehaene, Cohen, Sigman, & Vinckier, 2005), neurons at the lower level have smaller receptive fields and code elementary visual units which are converged at higher levels to lead to the identification of larger units. In this way, visual features are integrated into feature conjunctions and then into individual letters (i.e., integration of visual features into letters), which are further integrated into multi-letter units (e.g.,

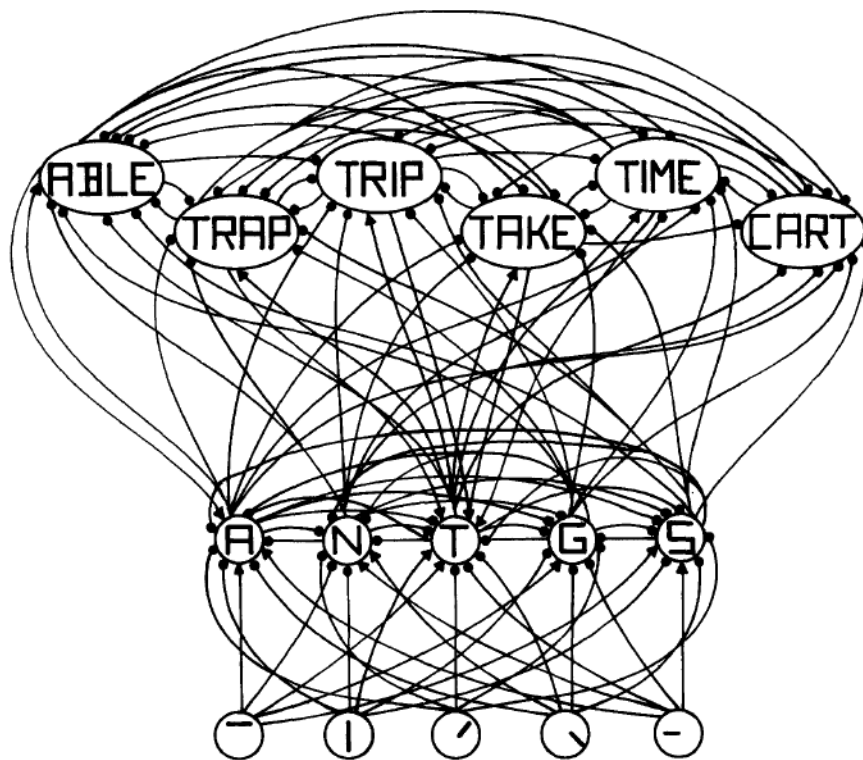


Figure 1-2. The Interactive Activation Model.

Visual features activate individual letters, and in turn words, via facilitatory, as well as inhibitory, connections. Adopted from McClelland & Rumelhart (1981).

bigrams) and eventually into whole words (i.e., integration of letters into letter strings).

In particular, expert print processing has been suggested to depend on the integration of letters into unified letter-string percepts called ‘visual word forms’ (for a review, see McCandliss, Cohen, & Dehaene, 2003). As empirical evidence, Frederiksen & Kroll (1976) showed that the speed of word recognition in adult readers remained constant with an increase in the number of constituent letters (i.e., word length). This result is in contrast with the pronounced length effect in children (Martens & de Jong, 2006; Zoccolotti et al., 2005), which reflects letter-by-letter processing. Moreover, many studies have demonstrated the more accurate identification of letters embedded in

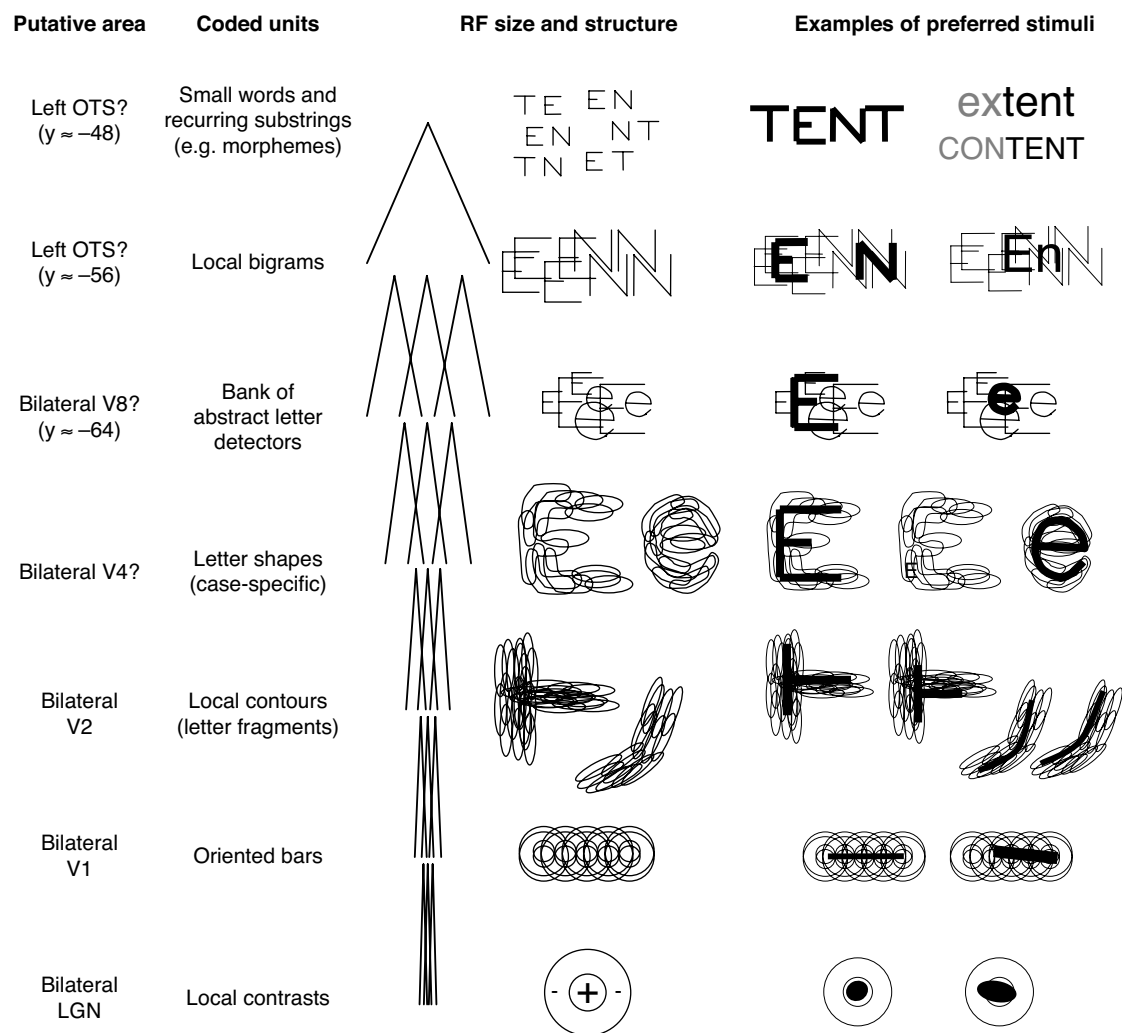


Figure 1-3. Neurobiological scheme of visual word recognition.

Visual neurons prefer increasingly larger units with moving up the hierarchy, and larger units may be represented by the convergence of activations at prior levels. Adopted from Dehaene et al. (2005).

briefly presented words (Reicher, 1969; Wheeler, 1970) and pseudowords (e.g., Chase & Tallal, 1990) compared to those in unpronounceable letter strings and letters in isolation (i.e., word/pseudoword superiority effect). These effects indicate that letters in words and pseudowords are processed in parallel; i.e., expert adult readers process a string of letters as a single object. These findings support the existence of early

processes to integrate letters into letter strings. Since a word/pseudoword superiority effect is not observed in dyslexic children (Chase & Tallal, 1990), it should be critical for fluent reading.

1.5. Print-tuned N170 Component of Event-Related Potentials

1.5.1. Overview of N170

N170 is a negative ERP component that peaks between 140 to 200 ms after stimulus presentation. It is elicited by visual stimuli in general and is distributed predominantly at occipito-temporal electrode sites. Importantly, N170 is strongly elicited by certain classes of visual stimuli that fall into the observer's domain of expertise, compared to visual control stimuli. Increased N170 has been observed in response to faces (e.g., Bentin, Allison, Puce, Perez, & McCarthy, 1996), animals in animal experts (Tanaka & Curran, 2001), and cars in car experts (Gauthier, Curran, Curby, & Collins, 2003). These findings indicate that extensive visual learning and experience alter early perceptual processes to be specifically tuned to visual stimuli that belong to the same category, which is referred to as perceptual expertise (for a review, see Palmeri et al., 2004).

1.5.2. Reading-related specialization of N170 and its neural substrate

Reading also involves a similar form of perceptual expertise, as evidenced by a specific enhancement of N170 in response to print stimuli. Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier (1999) were the first to report enhanced N170 in response to visual words, nonwords, and consonant strings relative to strings of alphanumeric symbols or geometric figures, which was predominant at the

left occipito-temporal site. The print-tuned N170 is also enhanced for print stimuli in well-learned script relative to that in response to novel script (Maurer, Zevin, & McCandliss, 2008; Simon, Bernard, Lalonde, & Rebaï, 2006). Furthermore, print-specific enhancement was mostly absent in children who had not yet started to learn to read (Maurer, Brem, Bucher, & Brandeis, 2005b). Therefore, the print-tuned N170 has been considered to reflect fast and specialized neural processing for print that develops through extensive reading experience.

Source localization studies of print-tuned N170 have identified its possible generator in a region of the left fusiform gyrus that is located in the inferior part of the occipito-temporal cortex (Brem et al., 2006, 2009; Maurer et al., 2005b). Functional neuroimaging studies have reported that this area shows increased activation in response to visual words and word-like letter strings, and is particularly sensitive to abstract properties of print stimuli (for a review, see McCandliss et al., 2003). Brain activation in this region, known as the VWFA, has also been shown to increase as reading skill increases (Shaywitz et al., 2002). Therefore, reading-related expertise reflected in the print-tuned N170 is most likely be correlated with neural activities in the VWFA.

1.5.3. Print-tuned N170 as an index of reading-related expertise

Previous studies of print-tuned N170 have linked it to reading-related expertise in the early stages of print processing, and were reviewed in Section 4.1. First, the print-specific enhancement of N170 is likely to be associated with the fast perceptual categorization of print stimuli. Print-tuned N170 typically differentiates both words and nonsense letter/character strings from visual control stimuli (Bentin et al., 1999; Mahé,

Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012; Maurer, Brandeis, & McCandliss, 2005a; Simon, Bernard, Largy, Lalonde, & Rebai, 2004), while sensitivities to lexical attributes have also been reported (Kim & Straková, 2012; Mahé et al., 2012; Maurer et al., 2005a; McCandliss, Posner, & Givon, 1997; Sereno, Rayner, & Posner, 1998). Along with previously-mentioned evidence of perceptual categorization (Nobre et al., 1994; Schendan et al., 1998), print-tuned N170 indicates that inputs of letter/character strings are classified as stimuli that represent print during early visual cortical processing.

Second, although the sensitivity of N170 in response to print stimuli may reflect one case of perceptual expertise out of a broader class of visual stimuli, such as faces and well-trained objects, there is also evidence that N170 print-tuning may be a special case. The print-specific enhancement of N170 is characterized by a left-lateralized topography (Bentin et al., 1999; Brem et al., 2009; Mahé et al., 2012; Maurer et al., 2005a; Simon et al., 2004), as opposed to N170 in response to faces and objects, which shows a bilateral or right-lateralized distribution (e.g., Rossion, Joyce, Cottrell, & Tarr, 2003). Based on the fact that phonological processing particularly recruits left-lateralized regions (Price, Moore, Humphreys, & Wise, 1997; Rumsey et al., 1997), this left-lateralization effect has been linked to phonological mapping processes. In fact, the left-lateralization of N170 is typically absent in children, in whom the phonological mapping skill is not yet fully developed (Kast, Elmer, Jancke, & Meyer, 2011; Maurer et al., 2006, 2007), and the regularity, or transparency, of spelling-to-sound correspondence has been shown to influence the extent of N170 left-lateralization in

adults (Maurer et al., 2005a, 2005b). These findings suggest that N170 is likely to index early phonological mapping that arises shortly after the input of print stimuli (Maurer & McCandliss, 2007).

Lastly, print-tuned N170 has been considered to reflect reading-related expertise at the level of processing letter/character strings (Maurer et al., 2005a). Although this possibility has not been tested explicitly, the VWFA, a possible generator of print-tuned N170, is particularly sensitive to ‘visual word forms’ rather than to the presence of letters (Cohen et al., 2002). This suggests that print-tuned N170 is also associated with processes to perceptually integrate letters/characters into a unified object. Although a print-specific enhancement of N170 has also been observed for alphabetic letters presented in isolation, it showed a bilateral distribution that was distinct from the print-tuned N170 for letter strings (Stevens, McIlraith, Rusk, Niermeyer, & Waller, 2013). Therefore, further examinations are necessary to clarify the relationships between the perceptual integration of print stimuli and reading-related expertise reflected in N170.

In summary, print-tuned N170 seems to be a suitable index for exploring the underlying mechanisms of expert reading; especially those that exist in the early stages of print processing. Thus, the present study focused on this particular ERP component to deal with questions regarding reading-related expertise, which will be discussed in the next section.

1.6. Purpose of the Study

1.6.1. Early print processing under rapid stimulus presentation

In previous studies, print-tuned N170 has been examined under conditions that are very far from those in normal reading. As reviewed previously, expert reading is characterized by incredible speed of up to several words per second (Jackson & McClelland, 1975). Under such conditions, the processing resource that can be allocated to each word is highly limited. In other words, the attention that is available for each letter/character or even word must be highly restricted. However, previous print-tuned N170 studies used very low stimulus presentation rates (i.e., one stimulus every few seconds). This may have left ample processing resources available for each stimulus, which may not be consistent with the conditions of normal reading (Kronsnabel, Schmid, Maurer, & Brandeis, 2013). Therefore, the early stages of print processing reflected in print-tuned N170 must be further examined under conditions that resemble normal reading. To this end, the present study used rapid stimulus presentation (i.e., two to three stimuli every second) to restrict the availability of attention to each stimulus.

1.6.2. Early stages of Hiragana string processing and print-tuned N170

The second issue with previous studies is that only a few have examined the early stages of print processing, or print-tuned N170, with Japanese Hiragana script. While many studies have considered alphabetic scripts and increasingly logographic Chinese characters (e.g., Lin et al., 2011; Wong, Gauthier, Woroch, DeBuse, & Curran, 2005), only a few have dealt with print in Hiragana. Hiragana is one of the three types of Japanese script (i.e., Hiragana, Katakana, and Kanji), and currently consists of 46 letters. With few exceptions, each Hiragana letter represents distinct syllables with an

equivalent duration (i.e., mora). Therefore, Hiragana script is characterized by highly consistent mapping to phonology based on relatively large grain units (syllables) compared to alphabetic or logographic scripts.

Regarding print-tuned N170, Maurer et al. (2008) found left-lateralized N170 for Hiragana words in adult Japanese readers, which was contrasted to a bilateral N170 in non-Japanese readers. Horie et al. (2012) reported left-lateralized N170 in response to Hiragana words and nonwords, in contrast to bilateral N170 for visual control stimuli. These findings suggest that the left-lateralized N170 is also associated with reading-related expertise with Hiragana script. However, as stated above, Hiragana script is distinct from other scripts in terms of grain unit and the transparency of phonological mapping. Considering that N170 left-lateralization may involve early phonological mapping processes (Maurer & McCandliss, 2007; Maurer et al., 2005a; Stevens et al., 2013), further research on the print-tuned N170 in highly transparent Hiragana script is necessary to clarify the early stages of print processing in this script.

1.6.3. Overview of the study

The present study aimed to investigate critical processes in fluent reading, namely, fast perceptual categorization, early phonological mapping, and the perceptual integration of letters into letter strings, in Hiragana script by examining the print-tuned N170. In three experiments, Hiragana strings were presented in rapid stimulus sequences, specifically at a rate of two to three stimuli per second. Although this rate is still lower than that in very fluent reading (Jackson & McClelland, 1975), it is comparable to a rate at which the attentional resources committed to stimulus

processing could be limited, particularly for unattended stimuli (Schwent, Hillyard, & Galambos, 1976).

Experiment 1 investigated the automaticity of fast perceptual categorization processes in terms of its independence from linguistic processes. To this end, Experiment 1 examined the print-tuned N170 for Hiragana strings that were completely task-irrelevant in rapid-presentation sequences. This condition was expected to minimize deliberate as well as unintentional linguistic processing due to a high information load (Schwent et al., 1976). Experiment 2 focused on the left-lateralization of print-tuned N170, which has been suggested to reflect the engagement of phonological mapping in the early phase of print processing (Maurer & McCandliss, 2007). With the same stimuli and presentation conditions as in Experiment 1, a task in Experiment 2 required attention to a stimulus attribute (i.e., color), which should allow us to examine if attention is necessary for N170 left-lateralization, or early phonological mapping processes. Experiment 3 explored if fast perceptual categorization processes in Hiragana script operate based on integrated letter-string percepts. The extent of the integration was examined by using an ERP spatial attention effect, which has been shown to decrease as the extent of perceptual grouping increases (e.g., Kasai, 2010). Overall, the study aimed to clarify the neural and psychological underpinnings of fluent reading in the Hiragana script.

2. Experiment 1

Fast Perceptual Categorization of Hiragana Strings under Restriction of Attention²

2.1. Introduction

The act of learning to read involves the development of fast neural processes that are tuned for print. A robust electrophysiological marker of such neural specialization is the occipitotemporal N170 component of ERPs, which peaks between 150 and 200 ms after stimulus presentation. N170 is likely to reflect visual expertise for print, which can be observed as two types of N170 effects: print tuning and sensitivity to lexical attributes. The former effect appears as a left-lateralized enhancement of N170 for word-like stimuli in contrast to nonlinguistic visual control stimuli such as symbol strings (Bentin et al., 1999; Maurer et al., 2005a; Simon et al., 2004). Although most previous studies have used alphabetic languages, N170 print tuning has also been observed with a nonalphabetic language (Chinese characters) (Wong et al., 2005). This effect has been suggested to reflect fast and automatic print processing as it has been observed consistently during nonlinguistic tasks (Bentin et al., 1999; Maurer et al., 2005a; Wong et al., 2005).

The latter effect, that is, N170 sensitivity to lexical attributes, has been observed as a contrast between words, pseudowords, and/or consonant strings (Kim & Straková, 2012; Maurer et al., 2005a; McCandliss et al., 1997), or words with different lexical frequencies (Sereno et al., 1998; Simon et al., 2004). This lexical effect is often

² Experiment 1 has been published as; Okumura, Y., Kasai, T., & Murohashi, H. (2014). Early print-tuned ERP response with minimal involvement of linguistic processing in Japanese Hiragana strings. *NeuroReport*, 25, 410–414.

observed during tasks that have linguistic demand. Source localization studies of print tuning have suggested that N170 is closely related to neural activities of an area in the left occipitotemporal cortex known as the VWFA (Brem et al., 2009; Maurer et al., 2005; McCandliss et al., 2003), which is also sensitive to lexical attributes, as with N170 (for a review, see McCandliss et al., 2003).

Experiment 1 aimed to clarify the necessity of explicit linguistic processing for N170 print tuning in a nonalphabetic language. Previous studies on N170 print tuning may have possibly involved task-irrelevant linguistic processing (Kronschabel et al., 2013). In those studies, the stimulus presentation rate was generally low (i.e. one stimulus every few seconds), and therefore, ample processing resources were available for each stimulus. This condition may favor automatic or even deliberate linguistic processing. Therefore, it seems important that we examine N170 print tuning under a further restriction of linguistic processing to investigate the automaticity of print processing, which the N170 print tuning reflects.

In Experiment 1, ERPs in response to rapidly presented Hiragana words, nonwords, and alphanumeric symbol strings were compared. Rapid stimulus presentation was used to restrict linguistic processing as it has been suggested to make it difficult or impossible for participants to process task-irrelevant information because of high information load (Schwent et al., 1976). Thus, by using a nonlinguistic task under rapid stimulus presentation, an early print-tuned ERP response for a nonalphabetic script could be examined with the minimal involvement of deliberate as well as automatic linguistic processing (Kronschabel et al., 2013). Hiragana is a Japanese syllabic script

that is characterized by highly transparent sound–letter correspondence, which can easily be processed in a phonological manner if linguistic processing is not restricted.

2.2. Methods

2.2.1. *Participants*

The participants were 12 monolingual native Japanese speakers (six men, age 19–25 years, mean 21.5 years). All were right-handed and had normal or corrected-to-normal vision. They all provided written informed consent as required by the Declaration of Helsinki, and the study was approved by the local ethics commission. Data from one participant were excluded from the analysis because of excessive artifacts; therefore, the final number of participants was 11.

2.2.2. *Stimuli*

The stimuli were 100 familiar Hiragana words (mean rated familiarity of 6.16 out of 7, $SD = 0.19$, according to the NTT database) (Amano & Kondo, 1999), nonwords, and alphanumeric symbol strings that consisted of four letters or symbols. Nonwords were constructed by shuffling the letters of the words at each position (i.e. the first letter of a word was replaced by that of another word, and so on), and all were pronounceable. Alphanumeric symbols were chosen as visual controls because they are nonlinguistic but familiar to Japanese readers. Fourteen different symbols were used to construct symbol strings (Figure 2-1A).

Stimuli were presented at the center of a computer monitor in black against a gray background. The viewing distance was 70 cm. Letters/symbols were aligned horizontally with no blank space in the dense condition, and one double-byte space,

roughly 1.23° , in the sparse condition (Figure 2-1B). This manipulation was introduced to examine the role of a physical/spatial stimulus property in an early print-tuned ERP response. Stimuli extended 2.05° to the left and right of a central fixation cross (0.41° by 0.41° , presented 1.21° below the stimulus in light gray color) in the dense condition and 3.93° in the sparse condition. Each letter/symbol measured roughly 0.9° by 0.9° .

Each stimulus was presented for 100 ms with a random interstimulus interval of 300–600 ms (50 ms/step, Figure 2-1C). Under such rapid presentation, ERPs overlap in response to successive stimuli. However, this overlap should not have systematic effects because of a randomized stimulus order and sufficient number of epochs to be averaged.

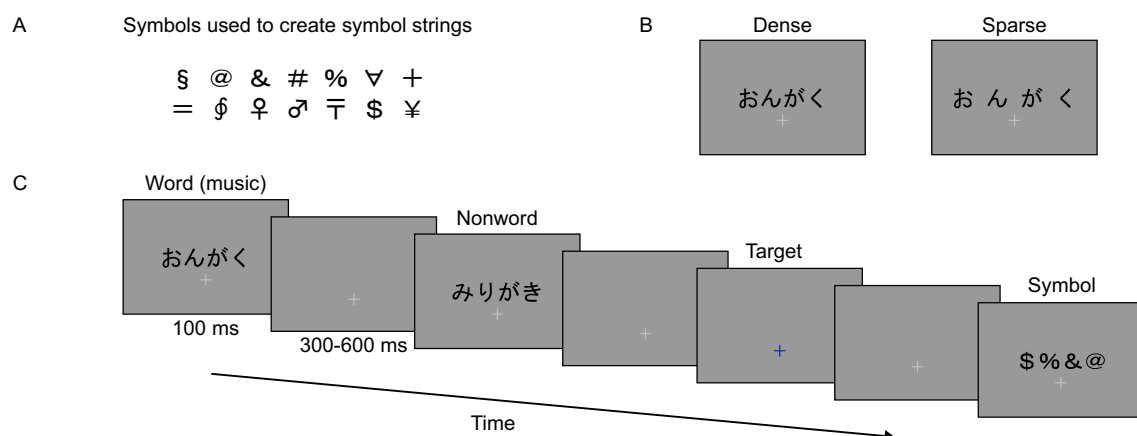


Figure 2-1. Stimuli and experimental procedure in Experiment 1.

(A) Fourteen alphanumeric symbols that were used to construct symbol strings. (B) An example of word stimuli in the two spacing conditions. (C) An example of a stimulus sequence in the dense condition. Participants detected a blue fixation cross among rapidly presented Hiragana words, nonwords, and strings of alphanumeric symbols.

2.2.3. Procedure

Participants were seated in a sound-proof and electrically shielded room and fixated on a central fixation cross during the experimental blocks. The fixation cross occasionally turned from light gray to blue (i.e. a target), and participants pressed a button as quickly as possible when they detected this change (Figure 2-1C). The dense and sparse conditions were presented in separate blocks in a counterbalanced order (three blocks each). In each block, 300 stimuli and 20 targets were presented in a random order, except that one participant received 30 targets. Stimulus presentation and response collection were controlled by E-prime software (version 2.0; Psychology Software Tools, Sharpsburg, Pennsylvania, USA). At the beginning of the experiment, participants received a short practice block in a spacing condition of the first experimental block.

2.2.4. Recordings and analysis

An electroencephalogram (EEG) was recorded using an electrode cap (Easycap GmbH, Herrsching, Germany) with 28 Ag/AgCl electrodes aligned according to the extended International 10–20 System (F7/8, F3/4, Fz, T7/8, C3/4, Cz, TP7/8, CP3/4, CPz, P7/8, P3/4, Pz, PO7/8, PO3/4, POz, O1/2, and Oz). All channels were referenced to the nose tip. The electrooculogram (EOG) was recorded bipolarly through electrodes placed at Fp1 and below the left eye (vertical) and at the outer canthi of both eyes (horizontal). The EEGs and EOGs were amplified using a SynAmps amplifier (NeuroScan, Sterling, Virginia, USA), filtered with a band-pass of 0.1–30 Hz, and sampled at 500 Hz. Electrode impedance was maintained below 10 k Ω . The continuous

EEG signals were divided into epochs from 200 ms before to 800 ms after stimulus onset and were baseline-corrected relative to the 200 ms prestimulus interval. Epochs with artifacts above 85 mV at any EEG or EOG channel and those immediately after the target were excluded before averaging. The mean numbers of epochs averaged for words (dense: 225, sparse: 224), nonwords (dense: 215, sparse: 224), and symbols (dense: 221, sparse: 223) were comparable, and a minimum of 140 epochs were averaged in each condition for all participants in the analysis.

The analysis focused on a posterior N1. On the basis of visual inspection of grand averages, N1 was quantified as the mean amplitude during the 160–220 ms interval at bilateral occipitotemporal (P7, P8) and parietal (P3, P4) sites. The mean amplitude of N1 was subjected to a four-way repeated-measures analysis of variance that included hemisphere (left, right), electrode site (occipitotemporal, parietal), spacing (dense, sparse), and stimulus type (word, nonword, symbol). The Greenhouse–Geisser correction was applied to contrasts with more than 1 degree of freedom.

2.3. Results

2.3.1. *Target detection*

Target detection was sufficiently quick and accurate, with a mean reaction time and hit rate of 361 ms ($SD = 40$) and 95.5% ($SD = 4.4$) in the dense condition, and 362 ms ($SD = 37$) and 96.8% ($SD = 2.5$) in the sparse condition. The number of false alarms was zero for all participants.

2.3.2. *Event-related potential data*

As shown in Figure 2-2, all stimuli elicited bilateral posterior N1 that was maximal

at occipitotemporal sites and more negative for words and nonwords than for symbols.

In an overall analysis of variance, a significant main effect of electrode site indicated a larger N1 at the occipitotemporal than the parietal site ($F(1, 10) = 13.73, p < 0.005$).

Also, there was a main effect of stimulus type ($F(2, 20) = 12.11, p < 0.001$). To examine print tuning and lexicality effects, a Tukey-corrected pairwise comparison was carried out. As a result, N1 for words and nonwords were significantly larger than that for symbols (word-symbol: $p < 0.001$, nonword-symbol: $p < 0.002$), whereas those for words and nonwords were comparable ($p > 0.8$). In terms of lateralization, there was no significant effect that involved hemisphere (all $ps > 0.2$).

Furthermore, there was a three-way interaction between electrode site, spacing, and stimulus type ($F(2, 20) = 6.24, p < 0.01$). To test the modulation of N1 by a physical stimulus property, the spacing by stimulus interaction was tested separately for electrode sites and was significant only at the parietal site ($F(2, 20) = 3.75, p < 0.05$). Further post-hoc tests performed separately for stimulus type showed that N1 for symbols was larger in the sparse condition than in the dense condition (Figure 2-2C, $F(1, 10) = 12.44, p < 0.006$).

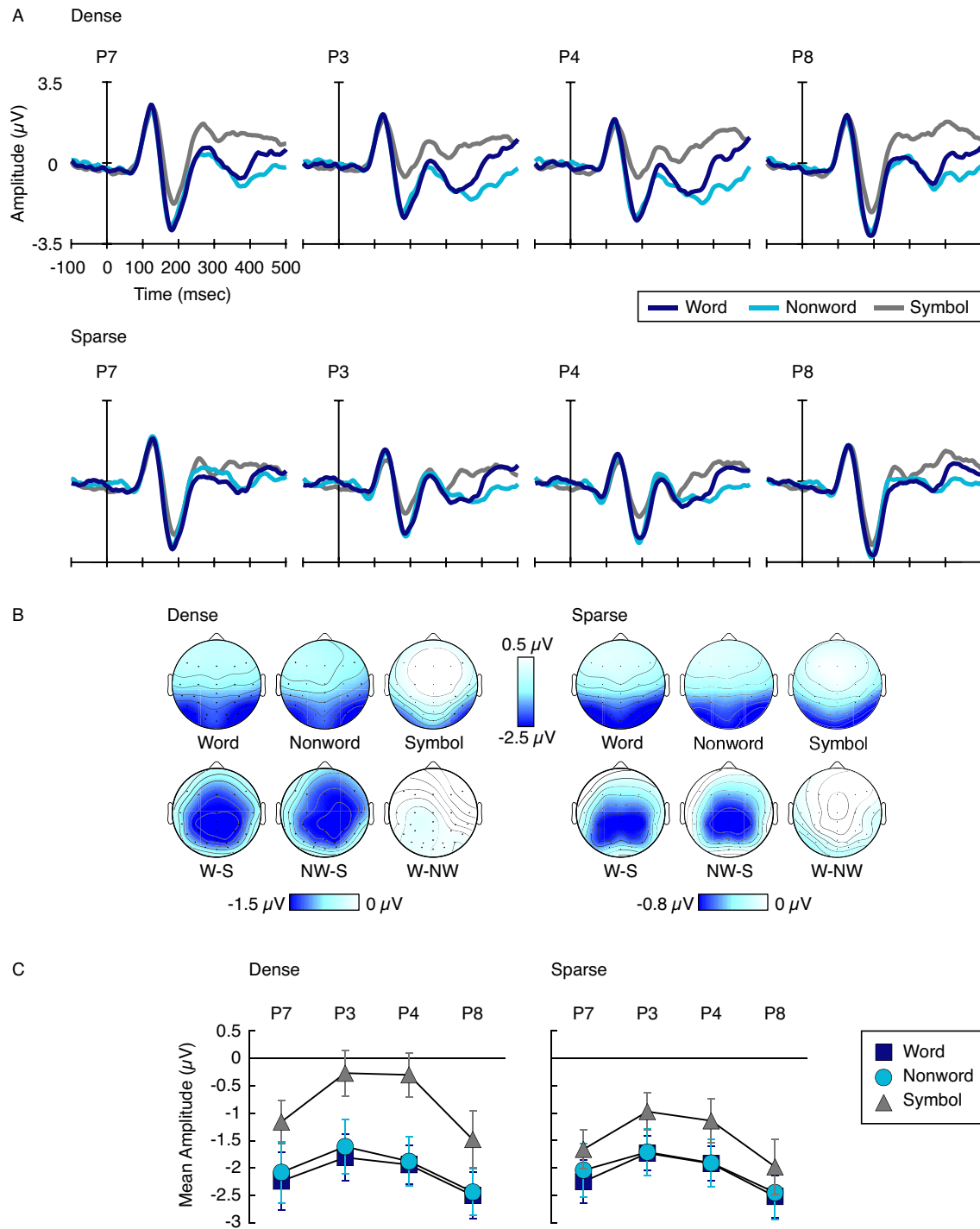


Figure 2-2. ERP results of Experiment 1.

(A) Grand-average ERPs at occipitotemporal (P7, P8) and parietal electrode sites (P3, P4). ERPs for each stimulus overlapped. (B) Topographic distribution of the mean amplitude of N1 during the 160–220 ms interval. W-S: Word minus Symbol. NW-S: Nonword minus Symbol. W-NW: Word minus Nonword (C) The mean amplitudes of N1 during the 160–220 ms interval. Error bars indicate standard errors of mean.

2.4. Discussion

Rapidly presented Hiragana strings elicited larger N1 than symbols, whereas there was no significant difference between words and nonwords. Under rapid stimulus presentation, a high information load is likely to result in the minimal involvement of task-irrelevant information processing (Schwent et al., 1976), in this case linguistic processing. The results of Experiment 1 show that N1 print tuning can be found in a nonalphabetic language without explicit linguistic demand, as defined by the task and presentation rate, in adults. The lack of sensitivity to lexicality may suggest the successful restriction of linguistic processing. These considerations strongly support the presence of fast and automatic print processing in expert readers of Japanese.

Although the specific enhancement for print was observed similarly, print-tuned N1 in Experiment 1 was distributed bilaterally as opposed to the left-lateralized N170 in previous studies (Bentin et al., 1999; Brem et al., 2006, 2009; Maurer et al., 2005a, 2005b; Simon et al., 2004; Wong et al., 2005). This may be because of the use of a nonalphabetic script. However, left-lateralized N170 for Hiragana words has been reported under slow stimulus presentation (Maurer et al., 2008). Although a direct comparison of lateralization results with those in previous studies is difficult, considering the non-comparable manner of data acquisition (e.g. number of channels), the lack of left lateralization in Experiment 1 might have resulted from the restriction of linguistic processing. As explicit grapheme–phoneme mapping may play a role in involving the cortical circuitry that supports left-lateralized N170 (Yoncheva, Blau, Maurer, & McCandliss, 2010), left lateralization of early print-tuned ERP responses

may depend on the amount of linguistic processes involved, whereas the specific enhancement observed for print does not.

In addition, there was no significant difference in N1 in response to words and nonwords between the dense and the sparse conditions. In terms of the distance between letters, spacing in the sparse condition should be comparable to or slightly greater than the 2.25 spaces (each letter measured 0.45°) used in the study by (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008), at which point the expert processing of print in the visual word form area started to be disturbed. The insensitivity of print-tuned N1 to interletter spacing may be further evidence of physical/spatial invariance of print-specific neural activities (Cohen et al., 2000; McCandliss et al., 2003), which suggests that print tuning takes place at the level of abstract representation. However, the enhanced N1 in response to symbols in the sparse condition suggests that non-expert processing of visual stimuli may be sensitive to physical/ spatial properties.

2.5. Conclusion

It is unclear whether or not this early print-tuned N1 is equivalent to the previously reported N170 for alphabetic or nonalphabetic languages. However, the finding in Experiment 1 supports the existence of fast neural processes in response to print that operate relatively independent of the influence of linguistic processing in nonalphabetic languages.

3. Experiment 2

Role of Visual Attention in Early Phonological Mapping³

3.1. Introduction

Extensive experience with a specific class of visual patterns confers a remarkable efficiency in categorizing, identifying, and recognizing those that fall into the class of the observer's expertise (Palmeri et al., 2004). These behavioral characteristics are often associated with class-specific neurophysiological responses that occur within 200 ms after stimulus presentation in ERPs, which have been demonstrated for faces (Bentin et al., 1996), and animals (Tanaka & Curran, 2001) and cars (Gauthier et al., 2003) when they are in an observers' domain of expertise.

Reading also involves a form of such expertise for letter or character strings (i.e., print), and a print-specific response is known as the N170 component. It is an occipito-temporal negativity that is enhanced for print in contrast to non-linguistic visual control stimuli such as symbols, typically during 140-200 ms post-stimulus (Bentin et al., 1999; Mahé et al., 2012; Maurer, Brandeis, et al., 2005; Simon et al., 2004). Such a neurophysiological marker may be useful for exploring how rapid and effortless reading becomes possible. In skilled adult readers, N170 elicited by print is typically larger at the left than at the right occipito-temporal site (Bentin et al., 1999; Horie et al., 2012; Lin et al., 2011; Maurer et al., 2008; Simon et al., 2004), or more prominently enhanced against control stimuli over the left hemisphere (Bentin et al., 1999; Brem et al., 2009; Mahé et al., 2012; Maurer et al., 2005a; Simon et al., 2004).

³ Experiment 2 has been published as; Okumura, Y., Kasai, T., & Murohashi, H. (2015). Attention that Cover Letters is Necessary for the Left-Lateralization of an Early Print-tuned ERP. *Neuropsychologia*. 69, 22-30

This left-lateralized topography is in contrast with that N170 for faces and objects exhibits a bilateral or right-lateralized distribution (e.g., Rossion, Joyce, Cottrell, & Tarr, 2003).

The print-specific enhancement of N170 has been observed across different types of print stimuli (Bentin et al., 1999; Mahé et al., 2012; Simon et al., 2004) and writing systems (Bentin et al., 1999; Lin et al., 2011; Maurer et al., 2005a; Maurer et al., 2008). Hence, it appears to be related to the visual expertise for print at a level of prelexical processing. In addition, source localization studies have suggested that the print-tuned N170 originates from the VWFA (e.g., Brem et al., 2006, 2009), a portion of the left fusiform gyrus that activates preferably to print stimuli (for a review, see McCandliss et al., 2003). These facts, along with the large body of studies, support that the print-tuned N170 and relevant VWFA activities are devoted to visual/orthographic processing that operate commonly across written language materials (Proverbio et al., 2007; Proverbio, Vecchi, & Zani, 2004; Proverbio, Zani, & Adorni, 2008; Simon, Petit, Bernard, & Rebaï, 2007; Tarkiainen, Helenius, & Hansen, 1999).

However, there have also been studies to indicate that the print-tuned N170, particularly the extent of its left-lateralization, is modulated by involuntary or learned phonological processes. For example, children who have learned letters but with developing phonological conversion skills show comparable N170 amplitude in both hemispheres (Kast et al., 2010) or bilateral increase in amplitude against visual control stimuli (Maurer et al., 2006; Zhao et al., 2014). In skilled adult readers, the consistency of letter-to-sound correspondences has been shown to influence N170 left-lateralization

for pseudowords, which was present in transparent German (Maurer, Brem, Bucher, & Brandeis, 2005b) but absent in opaque English (Maurer et al., 2005a). Furthermore, Yoncheva, Blau, Maurer, & McCandliss (2010) has demonstrated that explicit instruction of grapheme-to-phoneme correspondences is crucial for N170 left-lateralization in a newly learned artificial script. These findings indicate that the orthographic processing reflected in left-lateralized N170 could be modulated by phonological processes (Maurer & McCandliss, 2007; Price & Devlin, 2011; but see Lin et al., 2011), which predominantly recruit left-lateralized brain regions (Price et al., 1997; Rumsey et al., 1997).

The above notion predicts that early phonological mapping, or the N170 left-lateralization, occurs most pronouncedly for a transparent script in skilled adult readers. Japanese Hiragana is a highly transparent syllabic script, in which a given letter corresponds to a syllable almost in a one-to-one manner. Indeed, previous studies have also found left-lateralized N170 for Hiragana strings (words and nonwords: Horie et al., 2012; words: Maurer et al., 2008). However, Experiment 1 failed to find N170 left-lateralization for Hiragana strings when participants were asked to detect a change in the color of the fixation under rapid stimulus presentation. More specifically, Hiragana words and nonwords elicited larger occipito-temporal N1 than symbols equally at left and right hemisphere sites. This result suggests the absence of, or lesser engagement of, early phonological mapping under a condition in which attention to print stimuli are highly restricted, and it raises the possibility that early phonological mapping processes are not necessarily automatic. Importantly, while many studies have

observed left-lateralized N170 without an explicit demand for reading, their tasks always required judgments on some aspects of the print stimuli (e.g., size: Bentin et al., 1999; color: Lin et al., 2011; one-back: Brem et al., 2005, 2009; Maurer et al., 2005a; Maurer et al., 2005b; Maurer et al., 2008). In contrast, Experiment 1 required participants to attend to the fixation, rather than to the print stimuli. Therefore, attention to the print stimuli themselves seems to be critical for inducing N170 left-lateralization. One possible conceptual framework to this is object-based attention; attending to a feature of an object facilitates processing of other features that belong to the same object (Duncan, 1984), and the associated mechanism may play an important role in inducing early phonological mapping that could influence N170 activities. However, the null result regarding left-lateralization in Experiment 1 cannot solely support this notion.

The purpose of Experiment 2 was to test whether attention to print stimuli is necessary for N170 left-lateralization in Hiragana script by using the same stimuli and the presentation condition as in Experiment 1. The critical difference was that participants detected infrequent blue stimuli (targets) among frequent black stimuli (nontargets) in Experiment 2: such a task requires participants to discriminate or attend to color of print stimuli. ERPs in response to nontargets were examined to involve minimized effects of decision- and motor-related activities. According to previous ERP studies of visual selective attention, attention to nonspatial features (i.e., color or motion) elicits selection negativities (SNs), which start at around 200 ms after stimulus onset and reflect selective facilitation of feature specific activities (for a review, see

Hillyard & Anllo-Vento, 1998). Importantly, SNs occur only when stimuli are presented at an attended location, and spatial attention is associated with amplitude modulation of early P1 and N1 components, irrespective of attended or unattended feature values of stimuli (Anllo-Vento & Hillyard, 1996; Hillyard & Münte, 1984; but see Zhang & Luck, 2009). Therefore, spatial selection precedes feature selection, and the task to detect color-defined targets in Experiment 2 should lead spatial attention to print stimuli, even if they are nontargets. If early phonological mapping processes require attention to print stimuli, left-lateralized print-tuned ERP should be observed for nontarget Hiragana strings.

Furthermore, in Experiment 2, stimuli were presented in two different spacing conditions: dense condition with narrow spacing and sparse condition with wide spacing. Although the effect of spacing on left-lateralized N170 has not been studied previously, the print-tuned N1 in Experiment 1 was insensitive to this manipulation. Moreover, spacing has been shown to influence visual word processing (e.g., Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Risko, Lanthier, & Besner, 2011) and the neural activities of the VWFA, where left-lateralized N170 has been suggested to originate (e.g., Brem et al., 2006, 2009). Therefore, the manipulation of spacing may provide an opportunity to explore the role of physical/spatial stimulus properties in early print processing.

3.2. Methods

3.2.1. *Participants*

The participants were 22 monolingual native Japanese speakers (11 males; age

20-26 years, mean 22.5 years). All of the participants were right-handed and had normal or corrected-to-normal vision. They all gave their written informed consent as required by the Declaration of Helsinki, and the study was approved by the local ethics commission. Data from two participants were excluded from the analysis due to excessive artifacts; therefore, the final number of participants was 20.

3.2.2. *Stimuli*

The stimuli consisted of 107 familiar Hiragana words (mean rated familiarity of 6.15 out of 7, $SD = 0.19$, according to the NTT database; Amano & Kondo, 1999), nonwords, and alphanumeric symbol strings that consisted of four letters or symbols. Nonwords were constructed by shuffling the letters of the words at each position (i.e., the first letter of a word was replaced by that of another word, and so on), and all were pronounceable. Alphanumeric symbols were chosen as visual controls because they are non-linguistic but familiar to Japanese readers. Fourteen different symbols were used to construct symbol strings.

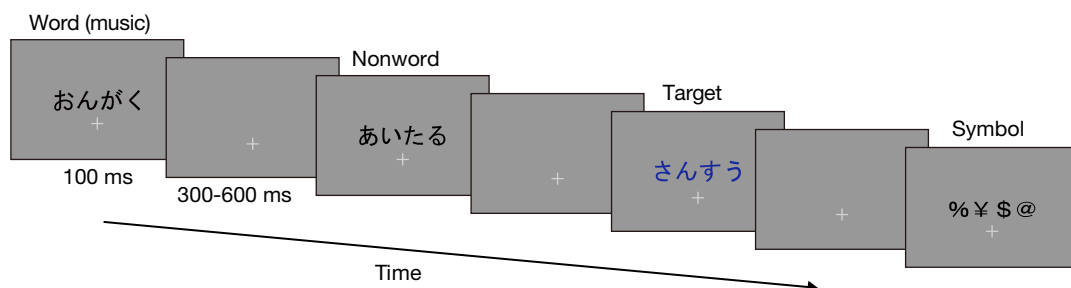


Figure 3-1. Stimuli and experimental procedures in Experiment 2.

For each type of stimulus, 100 nontarget and 7 target stimuli were presented in a black and blue font, respectively. All stimuli were presented against a gray background at the center of a computer monitor. A central light gray fixation cross (0.41° by 0.41°) was presented 1.21° below the stimulus, which remained on the monitor throughout the experiment. The viewing distance was 70 cm. Letters/symbols were aligned horizontally with no blank space in the dense condition, and with one double-byte space, roughly 1.23° , in the sparse condition. Stimuli extended 2.05° to the left and right of the central fixation cross in the dense condition and 3.93° in the sparse condition. Each letter/symbol measured roughly 0.9° by 0.9° .

Each stimulus was presented for 100 ms with a random ISI of 300 to 600 ms (50 ms per step, Figure 3-1). Under such rapid presentation, ERPs in response to a successive stimuli overlap. However, this overlap should not have systematic effects because of the randomized stimulus order and the sufficient number of epochs to be averaged.

3.2.3. Procedure

Participants were seated in a sound-proof and electrically shielded room and fixated on the central fixation cross during the experimental blocks. They were instructed to press a button as quickly as possible after the appearance of blue stimuli (i.e., targets, Figure 3-1). In each experimental block, 300 nontarget and 21 target stimuli were presented in random order, both of which consisted of equal numbers of words, nonwords, and symbol strings. The dense and sparse conditions were presented in separate blocks in a counterbalanced order, and the participants completed 3 blocks

in each condition. Stimulus presentation and response collection were controlled by E-prime software (version 2.0, Psychology Software Tools, Sharpsburg, PA, USA). At the beginning of the experiment, participants received a short practice block under the spacing condition of the first experimental block.

3.2.4. Recordings and analysis

Behavioral measures included the percentage of correct target detections (hits) and reaction times (RTs) for hits. Responses that occurred 150-800 ms after target presentation were classified as hits, and other responses were classified as false alarms (FAs). Mean hit rates and RTs were calculated separately for the spacing conditions and stimulus types. For the behavioral measures, since there were only 21 stimuli for each experimental condition, the Shapiro–Wilk test was used to determine if data sets could be modeled by a normal distribution. As a result, for RTs, the test supported the normality of the data in all conditions (all W s $> .93$, $ps > .17$); therefore they were submitted to a two-way repeated measures analysis of variance (ANOVA) including spacing (dense/sparse) and stimulus type (word/nonword/symbol). The Tukey correction was used for pairwise comparisons among stimulus types to avoid multi-comparison errors. However, the hit rates deviated from the normal distribution (all $ps < .001$), which may partly be due to the ceiling effect (Table 3-1).

An electroencephalogram (EEG) was recorded using an electrode cap (Easycap GmbH, Herrsching, Germany) with 28 Ag/AgCl electrodes aligned according to the extended International 10-20 System (F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, PO7, PO3, POz, PO4, PO8, O1, O2, and Oz). All

channels were referenced to the nose tip. The electrooculogram (EOG) was recorded bipolarly through electrodes placed at Fp1 and below the left eye (vertical) and at the outer canthi of both eyes (horizontal). The EEGs and EOGs were amplified by a SynAmps amplifier (NeuroScan, Sterling, USA), filtered with a band-pass of 0.1–30 Hz, and sampled at 500 Hz. Electrode impedance was kept below 10 k Ω .

The continuous EEG signals were divided into epochs from 200 ms before to 800 ms after the onset of nontarget stimuli, and were baseline-corrected relative to the 200 ms prestimulus interval. Epochs with artifacts above 75 μ V at any EEG or EOG channel and those immediately after the target were excluded before averaging. The mean number of epochs averaged for words (dense: 222, sparse: 217), nonwords (dense: 220, sparse: 220), and symbols (dense: 219, sparse: 217) were comparable, and a minimum of 130 epochs were averaged in each condition for all participants included in the analysis.

According to the focus of the study, analyses of ERP data focused on early components at posterior electrode sites that showed sensitivity to the stimulus type. For the first interval, 70-100 ms at Oz was chosen based on the visual inspection of grand-average ERPs (Figure 3-2A). The second interval was determined using difference waves for print specialization effect (i.e., amplitude difference between Hiragana strings and symbols), which was most prominent at occipitotemporal sites (P7, P8, see Figure 3-3B). Based on the first peak of the difference waves (Figure 3-3A), the interval was set to 130-170 ms poststimulus. For both intervals we computed mean amplitudes, which were subjected to repeated measures ANOVA that included spacing

(dense, sparse) and stimulus type (word, nonword, symbol). A hemisphere (left, right) factor was added for the latter time window. The Greenhouse-Geisser correction was applied to contrasts with more than 1 degree of freedom. Pairwise comparisons among stimulus types were Tukey-corrected, as with behavioral measures.

3.3. Results

3.3.1. *Target detection*

Reactions to targets were quick and highly accurate in both spacing conditions and for all stimulus types (Table 3-1). The number of false alarms was zero for all participants. For RTs, there was a significant main effect of stimulus ($F(2, 38) = 3.49$, $p < .05$), which was due to a significantly faster reaction for word targets than for symbol targets ($p < .04$). Neither the RT difference between words and nonwords ($p > .3$) nor that between nonwords and symbols ($p > .4$) were significant.

Table 3-1. Behavioral results of Experiment 2.

		Word	Nonword	Symbol
RT	Dense	348 (8)	352 (8)	355 (9)
	Sparse	366 (8)	365 (9)	373 (9)
Hit Rate	Dense	98.0 (0.5)	97.6 (1.0)	99.2 (0.4)
	Sparse	99.0 (0.4)	97.9 (0.6)	98.6 (0.5)

Response times (RT, msec) and Hit rates (%) are shown as a function of spacing and stimulus type. Standard errors are in parentheses.

3.3.2. *ERP data*

The earliest difference between print stimuli (i.e., words and nonwords) and symbol strings was observed as an occipital negativity with a peak latency at around 90 ms post-stimulus, and this effect was distributed predominantly over mesial occipital scalp regions (Oz, Figure 3-2). In an overall two-way ANOVA of mean amplitude during 70-100 ms post-stimulus, a main effect of spacing indicated that the negativity was greater in the sparse condition ($F(1, 19) = 12.98, p < .002$). There was also a main effect of stimulus type ($F(2, 38) = 3.84, p < .04$), and a pairwise comparison revealed that this negativity was greater for words than for symbols ($p < .04$). The differences between nonwords and symbols ($p > .1$), and words and nonwords ($p > .8$) were not significant. Although the effect of stimulus type seemed to vary somewhat between spacing conditions, their two-way interaction was not significant ($F(2, 38) = 0.74, p > .4$).

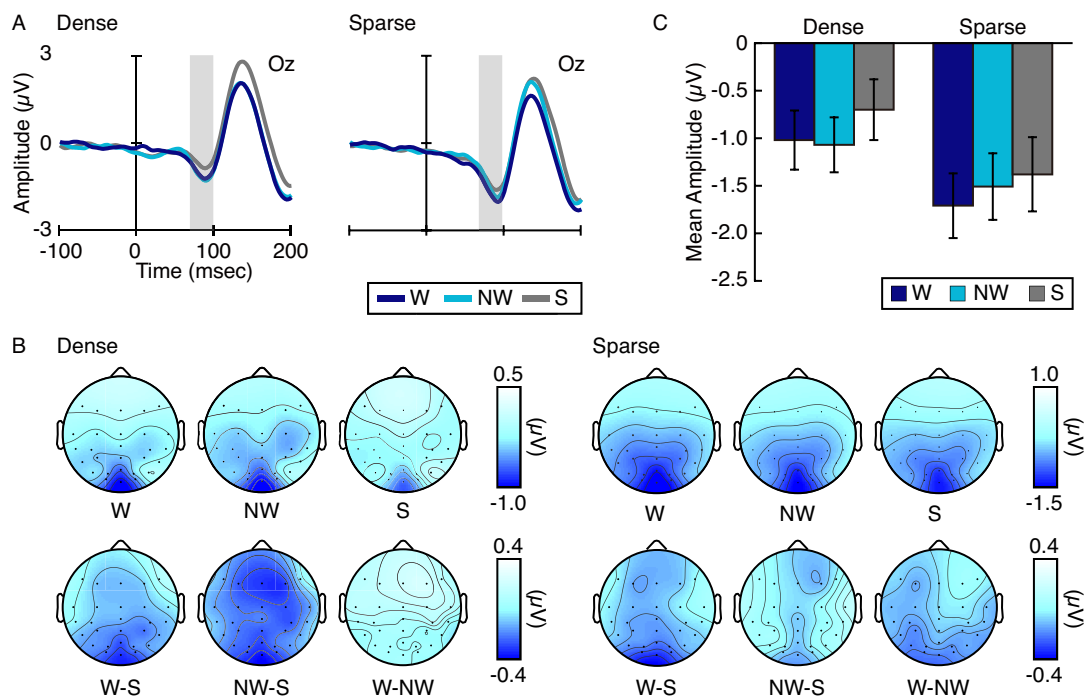


Figure 3-2. ERP results during 70-100 ms poststimulus (Oz) in Experiment 2.

(A) Grand-average ERPs at a mesial occipital site (Oz) for nontarget stimuli. ERPs for each stimulus overlapped. W: word. NW: nonword, S: symbol. Shaded regions indicate an interval of the mean amplitude. (B) Topographic distribution of the mean amplitude during the 70–100 ms interval after stimulus presentation (top), and the mean amplitude of the difference between stimulus types during the same latency range (bottom). (C) The mean amplitudes of the original waves during the 70-100 ms interval after stimulus presentation. Error bars indicate the standard errors of the mean.

In a later time window (130-170 ms), words and nonwords elicited more negative ERPs compared to symbols at occipito temporal sites (P7, P8, Figure 3-3), which was supported by a main effect of stimulus type ($F(2, 38) = 31.30, p < .001$). Pairwise comparisons showed more negative ERPs for word and nonwords than for symbols (both $ps < .001$), but there was no significant difference between words and nonwords ($p > .4$). These results support an overall tendency that prints elicited more negative ERPs than symbols.

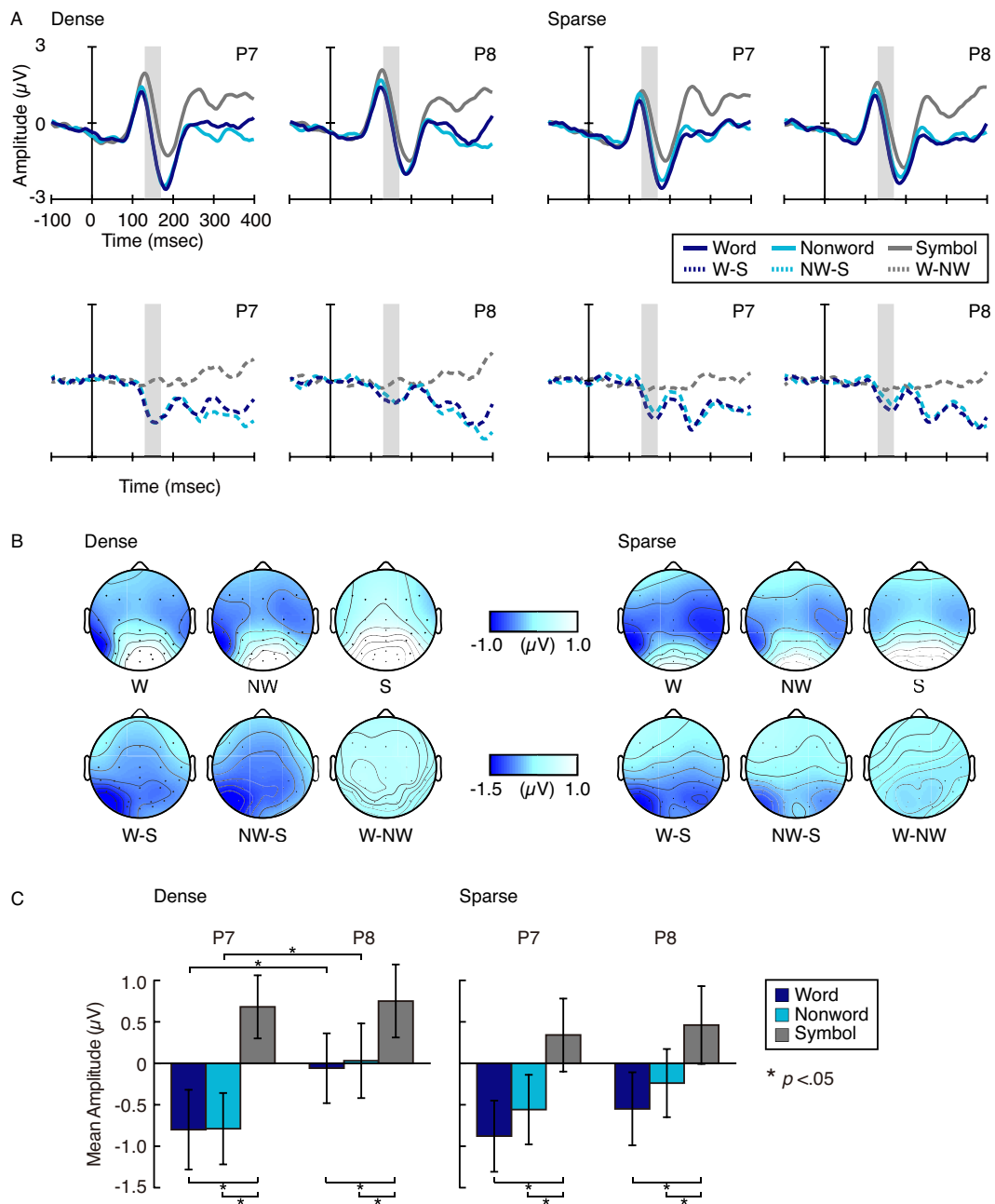


Figure 3-3. ERP results during 130-170 ms poststimulus (P7, P8) in Experiment 2. (A) Top: Grand-average ERPs at occipito-temporal sites (P7, P8) for nontarget stimuli. ERPs for each stimulus overlapped. Bottom: Difference waves for stimulus effect. W-S: word minus symbol. NW-S: nonword minus symbol. W-NW: word minus nonword. Shaded regions indicate the interval of the mean amplitude. (B) Topographic distribution of the mean amplitude during the 130–170 ms interval after stimulus presentation (top), and the mean amplitude of the difference between stimulus types during the same latency range (bottom). (C) The mean amplitudes of the original waves during the 130-170 ms interval. Error bars indicate the standard errors of the mean.

More importantly, this negative deflection for words and nonwords was more prominent at the left hemisphere site in the dense condition, whereas a hemispheric difference was not apparent in the sparse condition (Figure 3-3). This was reflected by a significant three-way interaction between spacing, hemisphere, and stimulus type ($F(2, 38) = 3.53, p < .04$). Post hoc analyses were conducted separately for the dense and sparse conditions. In the dense condition, hemisphere by stimulus type interaction was significant ($F(2, 38) = 5.79, p < .02$), and further post hoc tests for lateralization revealed that ERPs were more negative at P7 than at P8 for words ($F(1, 19) = 8.41, p < .01$) and nonwords ($F(1, 19) = 10.45, p < .005$), but not for symbols ($F(1, 19) = 0.91, p > .7$). Therefore, the results indicated a left-lateralization effect that is specific to prints. In the sparse condition, neither the hemisphere by stimulus type interaction ($F(2, 38) = 1.01, p > .3$) nor the effect of hemisphere ($F(1, 19) = 1.47, p > .2$) was significant, which reflected the lack of left-lateralization in this condition.

3.4. Discussion

To clarify the role of visual attention in early phonological mapping processes, Experiment 2 examined ERPs in response to transparent Japanese Hiragana strings by comparing them to ERPs in response to strings of familiar symbols that were rapidly presented and task-relevant. In contrast to Experiment 1 with the same conditions except for task-relevancy, Experiment 2 found a left-lateralized print-tuned response at 130-170 ms post-stimulus when the constituent letters were closely spaced. Moreover, unexpectedly, Experiment 2 found an enhanced early occipital ERP for words before

100 ms post-stimulus.

3.4.1. Attention is involved in N170 left-lateralization

In Experiment 2, the left-lateralization effect was found in the dense condition in addition to the print-specialization effect observed in Experiment 1. The present result supports our hypothesis that the orientation of visual attention to print itself is critical for triggering early phonological mapping processes, which the N170 left-lateralization likely reflects (Maurer et al., 2005a; Maurer & McCandliss, 2007; Stevens, McIlraith, Rusk, Niermeyer, & Waller, 2013). Although the fact that Hiragana strings elicited left-lateralized N170 is not novel by itself (Horie et al., 2012; Maurer et al., 2008), the contrast to the results of Experiment 1 confirms that the bilateral, or lack of left-lateralization of, print-tuned N1 in that study was not due to factors associated with stimuli or stimulus presentation, but rather to the task, in which letter strings were not task-relevant (i.e., discriminating fixation color). In Experiment 2, attention to the font color may have facilitated the processing of task-irrelevant print properties including phonological information, according to object-based attention mechanisms (Duncan, 1984). This finding is crucial because N170 left-lateralization, or the engagement of phonological mapping in print processing, is generally considered to be automatic in expert readers (for a review, see Frost, 1998; Halderman, Ashby, & Perfetti, 2012). Experiment 2 suggests, for the first time, that visual attention plays a role in an early phonological mapping process for transparent scripts. However, we must acknowledge that comparison across two studies has a limitation to this notion, and it must be further tested by directly manipulating tasks or attention in a single experiment.

The fact that the N170 left-lateralization was observed equally for words and nonwords suggests that phonological mapping engaged similarly in their processing. This appears to be inconsistent with the behavioral phenomenon, in which explicit phonological recording (i.e., reading aloud) is slower for nonwords (Frederiksen & Kroll, 1976) regardless of interletter spacing (Risko et al., 2011). However, masked phonological priming studies showed that very briefly presented letter strings, including pronounceable nonwords, do generate phonological information (Ferrand & Grainger, 1992, 1993; Grainger & Ferrand, 1994). In addition, transparent scripts tend to involve direct translation from letters to sounds, whereas opaque scripts rely more on whole words and lexical properties (Frost, 1998). Taken these together, it is possible that Hiragana words and nonwords induce phonological mapping similarly in early stages of processing, or at a prelexical level, which the N170 left-lateralization is likely to reflect.

In the results of Experiment 2, the difference between the two spacing conditions also supports the involvement of attention. Previously, interletter spacing has been suggested to control the way attention is deployed on print (Cohen et al., 2008; Risko et al., 2011; Risko, Stolz, & Besner, 2010). Specifically, the insertion of more than two letter spaces may induce the serial application of attention to the constituent letters, as evidenced by an increase in reading latency with the number of letters in words (i.e., length effect; Cohen et al., 2008; Risko et al., 2011). Thus, the lack of left-lateralization in the sparse condition in Experiment 2 may have been due to the serial application of attention. In fact, single letters are shown to elicit bilaterally enhanced N170 compared to control stimuli, which suggests less pronounced link to phonology during

single-letter processing (Stevens et al., 2013; Wong et al., 2005). In contrast, attention may have operated on Hiragana strings as units or objects in the dense condition, and activated other features of the strings.

The effect of spacing on the N170 left-lateralization is similar to response properties of VWFA that were found in neuroimaging studies. Vinckier et al. (2007) showed that anterior portions of the left fusiform area are activated preferably to larger chunk of letters such as quadrigrams and whole words. On the other hand, Cohen et al. (2008) demonstrated that increase in interletter spacing induce enhanced activation in posterior portions of the similar area bilaterally, which are suggested to be responsible for letter-level processing. Thus, although N170 does not necessary reflect such hemodynamic activities directly, VWFA may, at least partly, be involved in the N170 response for Hiragana strings observed in Experiment 2.

3.4.2. The earliest specialization for words

To the best of our knowledge, the word-symbol ERP difference at 70-100 ms after stimulus onset is the earliest sign of neural specialization for reading. It should not be due to low-level physical differences, since the constituents of nonwords were physically identical to those of words. Previously, a few ERP studies reported a very early differentiation of familiar vs. novel word forms that started at around 100 ms post-stimulus (Segalowitz & Zheng, 2009; Sereno et al., 1998), and sensitivity to lexical attributes has occasionally been found in print-tuned N170 (Kim & Straková, 2012; Mahé et al., 2012; Maurer et al., 2005a; McCandliss, Posner, & Givon, 1997). While most of the very early word-related responses were observed with tasks that require

access to word representation (e.g., lexical decision), Experiment 2 showed that it can be detected without an explicit demand for reading. The present early word-related response may have been observed because the rapid-presentation paradigm enabled a large number of epochs to be averaged, although we did not find this effect in Experiment 1. Previous studies have showed that attention to visual/orthographic properties enhances early sensory processing of print, as reflected by enhancement of occipital C1 (Proverbio & Adorni, 2009) and posterior N150 (Spironelli & Angrilli, 2007). The present finding may extend this notion that attention do not just enhance early sensory processing in general, but also facilitate very early neural specialization for processing words in Hiragana script.

Interestingly, the present behavioral results indicate more efficient color feature extraction in words than in symbols. Previous behavioral and neuropsychological studies of object-based attention have suggested that attention spreads over the whole region of words in comparison with nonwords (Kumada & Humphreys, 2001; Li & Logan, 2008; Liu, Wang, & Zhou, 2011). Although the task to discriminate font color should be possible with the detection of local parts in letter strings, activation of the whole word may have been beneficial for color discrimination.

Based on the present ERP and behavioral results, two types of object-based attention may be associated with print processing: the obligatory activation of low-level features based on words and the activation of relatively higher-level features (i.e., phonology) based on grouped letters, which may be reflected by very early (around 80-90 ms) or relatively early (N170) visual cortical processing, respectively.

3.5. Conclusion

The results of Experiment 2 are consistent with previous studies that have suggested the existence of expertise associated with familiar patterns of letters in early visual processing. The same differences between symbols and words or nonwords are consistent with left-lateralized N170 for other transparent scripts (Bentin et al., 1999; Maurer et al., 2005b). On the other hand, the results lead to novel findings: 1) early stages of print processing are not necessarily automatic, and 2) deployment of attention to letter strings triggers the obligatory activation of features that belong to the strings. Relationships between such early involuntary processes and those in later stages, as well as so-called phonological areas in the brain (e.g., angular and supramarginal gyrus, Booth et al., 2004) would be a future topic, although it is still unclear whether the present finding is limited to transparent Hiragana strings. Since deficits in visual attention have been suggested to be a cause of developmental dyslexia (for a review, see Vidyasagar & Pammer, 2010), clarifying how visual attention contributes to expert as well as impaired reading is an important subject.

4. Experiment 3

Unit of Print Representation in Fast Perceptual Categorization

4.1. Introduction

Extensive practice and experience with reading leads to remarkable speed and efficiency in processing visually presented letters, words, and word-like strings of letters. Such fluent reading has been considered to rest on a process that integrates the letters of a word into a unified percept. Behaviorally, this has been evidenced by a relatively constant speed of word recognition across different word lengths (i.e., the number of letters in a word) in expert adult readers (Frederiksen & Kroll, 1976). As another evidence, letters embedded in briefly presented words (Reicher, 1969; Wheeler, 1970) and pseudowords (e.g., Chase & Tallal, 1990) have been shown to be identified more accurately than those in unpronounceable letter strings or those presented in isolation, which is known as the word/pseudoword superiority effect. These behavioral phenomena support the notion that letters within letter strings are processed in parallel; i.e., letter strings are processed as a unitary object.

Neuroimaging and electrophysiological studies of visual word processing have demonstrated that the perceptual integration of letters into a unified percept plays a crucial role in reading-related neural specialization. In expert adult readers, a portion of the left fusiform gyrus, known as the VWFA, activates preferably in response to learned letter stimuli across different lexical attributes, while it distinguishes poorly structured letter strings (i.e., consonant strings) from well-structured words (e.g., Cohen et al., 2002; Fiebach, Friederici, Müller, & von Cramon, 2002; for a review, see McCandliss et al., 2003). This result shows that the functional specialization of the VWFA is linked

to a level of print processing that involves integrated letter-string percepts. In ERPs, a large body of evidence has shown that letter strings elicit enhanced N170 relative to non-linguistic visual control stimuli, such as strings of symbols and forms, typically during 140-200 ms poststimulus at occipito-temporal electrodes (Bentin et al., 1999; Mahé et al., 2012; Maurer, 2005a; Simon et al., 2004). The N170 amplitude and/or enhancement for letter strings is characterized by a left-lateralized topography that is distinct from bilateral or right-lateralized N170 in response to non-linguistic objects (e.g., Bentin et al., 1996; Gauthier et al., 2003; Tanaka & Curran, 2001) and single letters (Stevens et al., 2013). According to the source localization studies, this letter-string specific N170 is most likely to be originated from the VWFA (Brem et al., 2006, 2009). Therefore, the left-lateralized N170 for letter strings, a widely-accepted index of reading expertise, appears to arise based on unitary letter-string percepts that serve as a fundamental unit of the fast perceptual categorization processes that it reflects.

In contrast to the above findings, however, our previous experiments have identified N170 specializations for Hiragana strings that show a bilateral topography, under rapid stimulus presentation. Such a response was observed when participants were asked to detect a change in the color of the fixation cross (Experiment 1) and when the interletter spacing was wide (Experiment 2). These findings suggest that the bilateral N170 enhancement for Hiragana strings occurs when the construction of unitary letter-string percepts is hindered. For instance, Experiment 1 lacked focal spatial attention to Hiragana strings, whereas attention is crucial for the integration of features (Treisman & Gelade, 1980). Wide interletter spacing has been suggested to reduce the

physical integrity of letter strings and to lead to letter-by-letter processing (Cohen et al., 2008; Risko et al., 2010, 2011). However, previous experiments did not test or clarify the integrity of Hiragana letters and its nature.

The present experiment examined whether the bilateral N170 specialization for widely spaced Hiragana strings is associated with processing of, or underlying representations of, separate letters or unified letter strings, by using a spatial attention paradigm of ERPs. Directing of attention to a specific location within a visual field enhances early visual ERP components, such as posterior P1 and N1, over hemispheres contralateral to the attended location (i.e., lateralized spatial attention effect) in sustained-focal attention tasks with bilateral stimulus arrays (Heinze, Luck, Mangun, & Hillyard, 1990; Heinze et al., 1994; Kasai, 2010; Kasai & Takeya, 2012). In this paradigm, when bilateral stimuli are grouped or connected, attention spreads over the entire region of the stimuli, as reflected by worse behavioral performance (i.e., discrimination of stimuli at either hemifield) and decreased N1 spatial attention effects for connected stimuli compared to separate stimuli (Kasai, 2010; Kasai & Takeya, 2012). Thus, this paradigm may be useful for exploring the extent to which bilateral stimuli are grouped and its underlying neural processes.

In the current experiment, Hiragana words, nonwords, and alphanumeric symbol strings were bilaterally presented with wide spacing, as in the sparse condition in Experiments 1 and 2. Thus, it was expected that bilateral N170 enhancements for Hiragana strings would be elicited. Participants were instructed to attend to either the left or right end of the stimuli and to press a button if a letter or symbol with a

designated local visual feature (i.e., a target) appeared at the attended location. If widely-spaced Hiragana letters obligatorily have integrated representations, N1 lateralized spatial attention effects may decrease for words and nonwords in comparison with symbol strings, and behavioral performance of discriminating targets at the left or right ends of strings should be worse for words and nonwords. Since the previously-reported N1 lateralized attention effect is quite similar in latency and topography to the specific enhancement of N170 in response to letter strings, it was expected that spatial attention could modulate the print processing reflected in N170.

4.2. Methods

4.2.1. *Participants*

Twelve volunteers (6 males; age 19-38 years, mean 22.7 years) participated in the experiment. All participants were right-handed monolingual native Japanese speakers and had normal or corrected-to-normal vision. They all gave their written informed consent as required by the Declaration of Helsinki, and were paid for their participation. The study was approved by the local ethics committee.

4.2.2. *Stimuli*

The stimuli consisted of 100 familiar Japanese Hiragana words (mean rated familiarity of 6.01, $SD = 0.22$, according to the NTT database; Amano & Kondo, 1999), nonwords, and alphanumeric symbol strings that consisted of four letters or symbols. Nonwords were constructed by shuffling the letters of the words at each position (i.e., the first letter of a word was replaced by that of another word, and so on), so that the characters used and frequencies of each character were controlled between the word and

nonword sets. All nonwords were pronounceable. Alphanumeric symbols were chosen as visual controls because they are non-linguistic but familiar to Japanese readers.

Seventeen different symbols were used to construct symbol strings. Hiragana letters and symbols used in the experiment were classified into two types: those with two parallel horizontal lines (i.e., targets, Figure 4-1A) and those with no such visual feature. Sets of words, nonwords and symbol strings each consisted of 76 stimuli with no targets, 12 with a target at the left end, and 12 with a target at the right end.

Stimuli were presented in black against a gray background at the center of a computer monitor situated 70 cm in front of the participants (Figure 4-1B). The four constituents were aligned horizontally across the left and right hemifields, which extended 3.93° to the left and right of a central fixation cross (0.57° by 0.57° , presented 1.23° below the stimulus). Each letter/symbol extended roughly 1.06° horizontally and vertically. Each stimulus was presented for 100 ms with a random interstimulus interval (ISI) of 300 to 600 ms (50 ms per step), and the central fixation cross remained on the monitor throughout the experiment. Under such rapid presentation, ERPs in response to a successive stimuli overlap. However, this overlap should not have systematic effects because of the randomized stimulus order and the sufficient number of epochs to be averaged.

4.2.3. Procedure

Participants were seated in a sound-proof and electrically shielded room and maintained their fixation on a central fixation cross during the experimental blocks. At the beginning of each block, they were asked to direct their attention to a letter/symbol

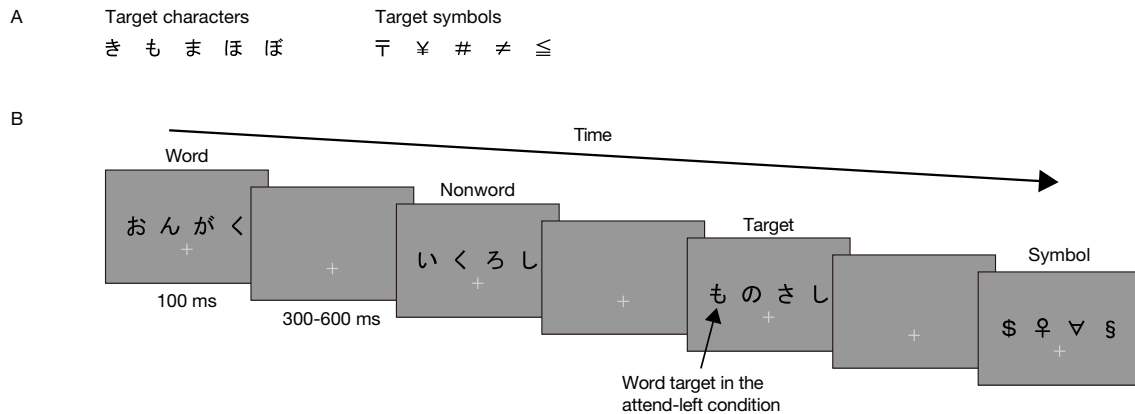


Figure 4-1. Stimuli and experimental procedures in Experiment 3.

(A) Target letters and symbols presented at either the left or right end of stimuli. They are defined as those that contain two parallel horizontal lines. (B) An example of a stimulus sequence.

at either the left or right end of the stimuli and to press a button as accurately and quickly as possible when a target appeared at the attended location (attended target). The button was pressed with their right thumb. Stimuli with no target (standards) and with a target at the ignored end (unattended targets) did not require a response.

Four attend-left and four attend-right blocks were presented in an alternating and counterbalanced order. Each block consisted of 300 stimuli (76 standards, 12 attended targets, and 12 unattended targets for each kind of stimulus) with a short break after every 100 stimuli. Therefore, participants received a total of 304 standards, 48 attended targets, and 48 unattended targets in each attention condition. Stimulus presentation and response collection were controlled by E-prime software (version 2.0, Psychology Software Tools, Sharpsburg, PA, USA). At the beginning of the experiment, participants received one block of practice with half of the trials in the attend-left condition and the other half in the attend-right condition to stabilize task performance

and eye movement. The stimuli used in the practice were the same as those in the main experiment.

4.2.4. *Recordings and analysis*

Button presses were classified as hits or false alarms. Hits were defined as the first response between 300 to 1000 ms after the presentation of attended targets, and any other responses were classified as false alarms. The mean reaction time (RT) for hits, hit rate, and false alarm rates were calculated and subjected to two-way repeated measures analyses of variance (ANOVA) with the attended hemifield (attend-left, attend-right) and stimulus (word, nonword, symbol) as factors. For false alarms, a type factor (standard, unattended) was also included. The Tukey correction was used for pairwise comparisons among stimulus types to avoid multi-comparison errors.

The electroencephalogram (EEG) was recorded using an electrode cap (Easycap GmbH, Herrsching, Germany) with 28 Ag/AgCl electrodes aligned according to the extended International 10-20 system (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, PO7, PO3, POz, PO4, PO8, O1, Oz, O2). All channels were referenced to the nose tip. Blinks and eye movements (electrooculogram, EOG) were recorded bipolarly through electrodes placed at Fp1 and below the left eye (vertical) and at the outer canthi of both eyes (horizontal). The EEGs and EOGs were amplified by a SynAmps amplifier (NeuroScan, Sterling, USA), filtered with a band-pass of 0.1–30 Hz, and sampled at 500 Hz. Electrode impedance was kept below 10 k Ω . The continuously recorded EEG signals were divided into epochs starting at 200 ms before and ending at 800 ms after stimulus onset. Epochs with artifacts above 85 μ V

at any EEG or EOG channel were automatically rejected. Epochs with false alarms, misses, and those immediately after a response were also excluded before averaging. ERPs were averaged separately for the type (standard, attended target, unattended target), attended hemifield, and stimulus. Baseline correction was applied to all time-points by subtracting the mean amplitude during the 200 ms prestimulus interval. The mean numbers of epochs averaged for standard words (attend-left: 232, attend-right: 227), nonwords (attend-left: 232, attend-right: 228), and symbols (attend-left: 234, attend-right: 230) were comparable, and the minimum was 185 per condition for all participants included in the analysis.

Analyses of ERP data were conducted on those for standards and focused on early visual components at posterior electrode sites. Based on the visual inspection of grand-average waveforms and difference waves for attention and stimulus effects (Figure 4-3), ERPs were quantified as mean amplitudes during 100-130 ms for P1 (PO7, PO8), 130-160 ms for early N1 (P7, P8), and 160-210 ms for late N1 (P7, P8). Mean amplitudes were subjected to three-way repeated measures ANOVA with attended hemifield, stimulus, and hemisphere (left, right) factors. The Greenhouse-Geisser correction was applied to contrasts with more than 1 degree of freedom. Pairwise comparisons among the three kinds of stimuli were Tukey-corrected, as with behavioral measures.

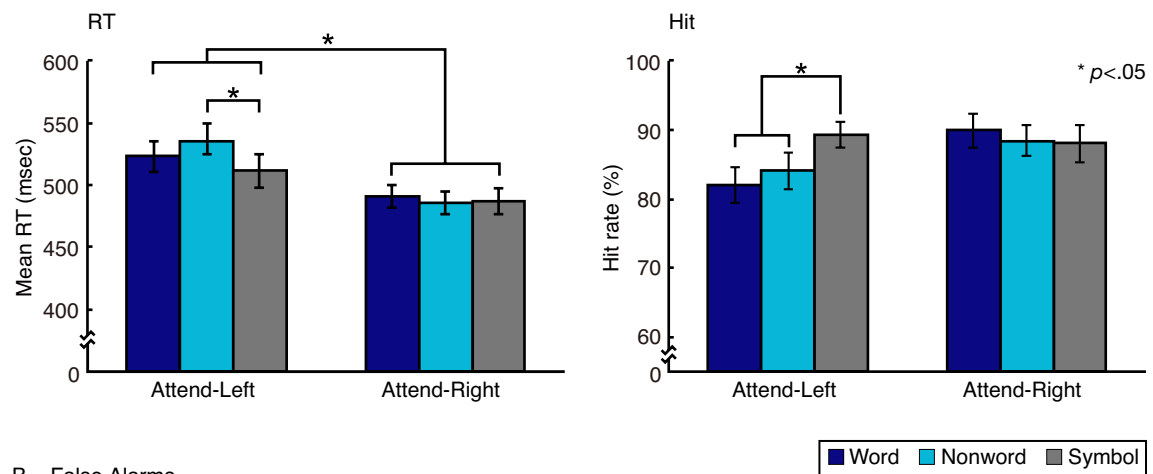
4.3. Results

4.3.1. Behavioral Results

Figure 4-2 shows the behavioral results. With regard to RTs (Figure 4-2A), faster responses in the attend-right than in the attend-left condition were reflected by a main effect of attended hemifield ($F(1, 11) = 26.48, p < .001$). There was also an attended hemifield by stimulus interaction ($F(2, 22) = 5.74, p < .01$), which was due to longer RTs for nonwords than for symbols only in the attend-left condition ($p < .004$). Similarly, hit rates (Figure 4-2A) were overall higher in the attend-right condition ($F(1, 11) = 6.48, p < .03$), and there was also a significant attended hemifield by stimulus interaction ($F(2, 22) = 4.63, p < .03$). Post hoc analyses revealed a simple main effect of stimulus only in the attend-left condition ($F(2, 22) = 4.78, p < .02$), which was due to lower hit rates for words and nonwords than for symbols (word vs. symbol: $p < .04$, nonword vs. symbol: $p < .05$).

With regard to FAs (Figure 4-2B), only a main effect of stimulus was significant ($F(2, 22) = 3.53, p < .05$), which was due to lower FAs for symbols than for nonwords ($p < .04$).

A Target Detection



B False Alarms

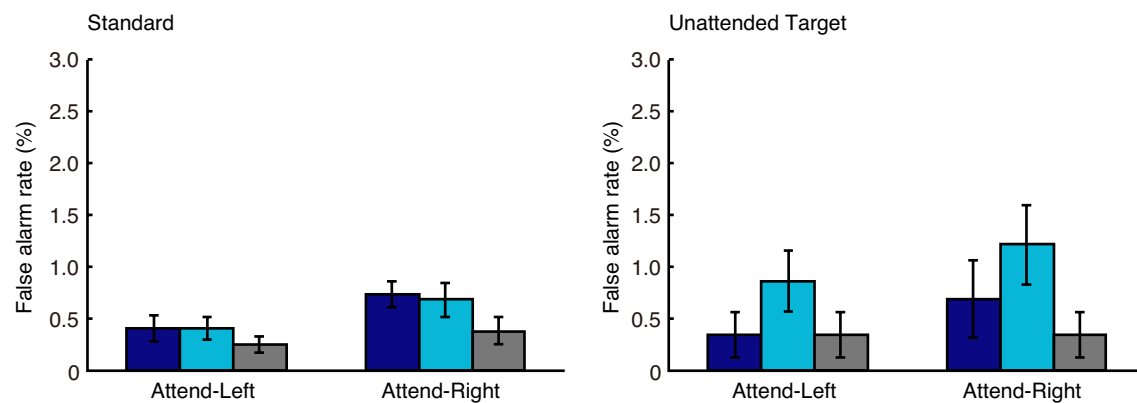


Figure 4-2. Behavioral results of Experiment 3.

(A) Mean reaction times (left) and hit rates (right) of target detection. (B) False alarm rates for standard stimuli (left) and for stimuli with a target letter/symbol at the unattended location (right). Error bars indicate the standard errors of the mean.

4.3.2. ERP data for standard stimuli

In grand-averaged ERPs for standards, spatial attention effects were revealed as differences in P1 and N1 amplitudes between the attend-left and attend-right condition, which were predominant at occipito-temporal scalp regions (Figure 4-3). Enhancements of N1 for words and nonwords against symbol strings were also predominant at occipito-temporal sites. Table 4-1 summarizes the p values of overall ANOVAs.

In the P1 latency range (100-130 ms), ERPs at PO8 were more positive in the attend-left than in the attend-right condition, while no such difference was observed at PO7 (Figure 4-3A). These were reflected by a significant attended hemifield by hemisphere interaction ($F(1, 11) = 5.62, p < .04$) with a significant simple main effect of the attended hemifield only at PO8 ($F(1, 11) = 12.18, p < .006$), as shown in Figure 4-5A. The topographic distribution of this asymmetric P1 attention effect is shown in Figure 4-4. No contrast involving stimulus factor was significant in this latency range (all $ps > .2$).

Table 4-1. Summary of statistical results for ERPs in the Experiment 3.

	P1 PO7/8 100-130 ms	Early N1 P7/8 130-160 ms	Late N1 P7/8 160-210 ms
Standards			
Attended hemifield	.012		.049
Hemisphere			
Stimulus		.012	.022
Attended hemifield $\times$ Hemisphere	.037		.015
Attended hemifield $\times$ Hemisphere $\times$ Stimulus			

All significant p values of overall ANOVA for mean amplitude during selected latency ranges are shown.

As shown in Figure 4-3B, ERPs for words and nonwords started to diverge from that for symbols in a negative direction shortly after the P1 peak, which affected the overall N1 amplitude. Meanwhile, N1 at P7 had greater amplitude when participants attended to the contralateral hemifield, but such an amplitude difference was not observed at P8. Interestingly, the onset of the N1 enhancement for Hiragana strings was approximately 30 ms earlier than that of the lateralized spatial attention effect (see P7 in Figure 4-3B). Therefore, the N1 latency range was divided into early (130-160 ms) and late (160-210 ms) phases for further analyses.

In the early N1 latency range (130-160 ms, Figure 4-5B), there was a significant main effect of stimulus ($F(2, 22) = 6.45, p < .02$). Pairwise comparisons showed more negative ERPs for words and nonwords than for symbols (both $ps < .02$), but no significant difference between words and nonwords ($p > .9$). No effects involving hemisphere were significant (all $ps > .3$), which indicated a bilateral distribution of this print-tuning effect in this latency range (Figure 4-4).

In the late N1 latency range (160-210 ms, Figure 4-5C), a main effect of stimulus was also significant ($F(2, 22) = 5.10, p < .03$), which involved the same contrasts among stimuli as the early N1 (word vs. symbol: $p < .03$, nonword vs. symbol: $p < .04$, word vs. nonword: $p > .9$). This print-tuning effect, again, did not interact with hemisphere (all $ps > .3$, Figure 4-4). Moreover, there was a significant attended hemifield by hemisphere interaction ($F(1, 11) = 8.19, p < .02$). As shown in the Figure 4-5C, it was due to greater N1 amplitude in the attend-right than in the attend-left condition at P7 ($F(1, 11) = 14.63, p < .003$), while an effect of attended hemifield was

not significant at P8 ($F(1, 11) = 0.78, p > .3$). The topographic distribution of this asymmetric late N1 attention effect is shown in Figure 4-4.

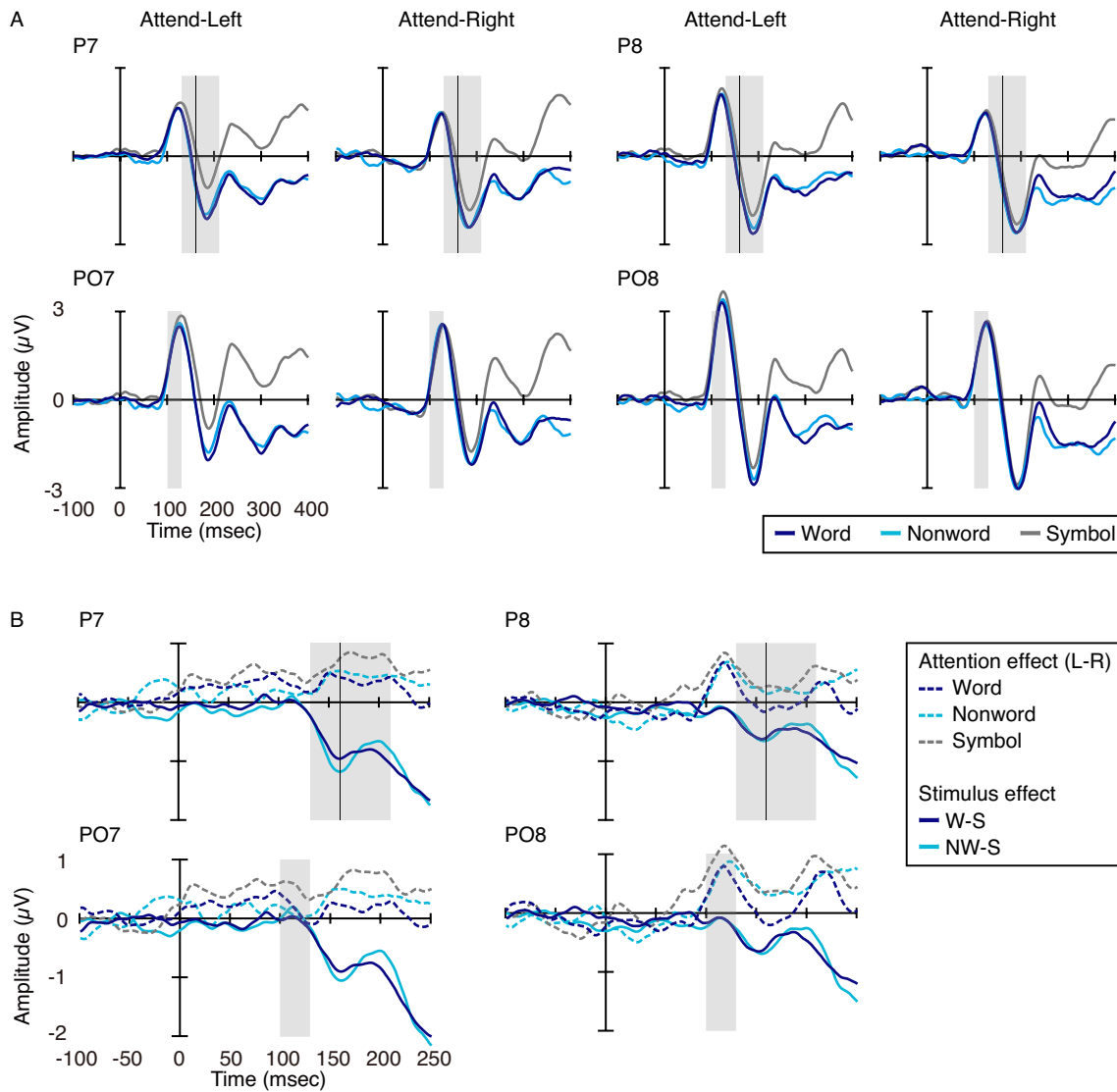


Figure 4-3. Grand-average ERPs in Experiment 3.

(A) Grand-average ERPs at occipito-temporal sites (P7, P8; PO7, PO8) for standards. ERPs for each stimulus overlapped. (B) Solid lines: Difference waves for the stimulus effect (W-S: word minus symbol, NW-S: nonword minus symbol). Attended hemifields were collapsed. Dashed lines: Attention effect for each type of stimulus (L-R: attend-left minus attend-right). Shaded regions indicate the interval of the mean amplitude.

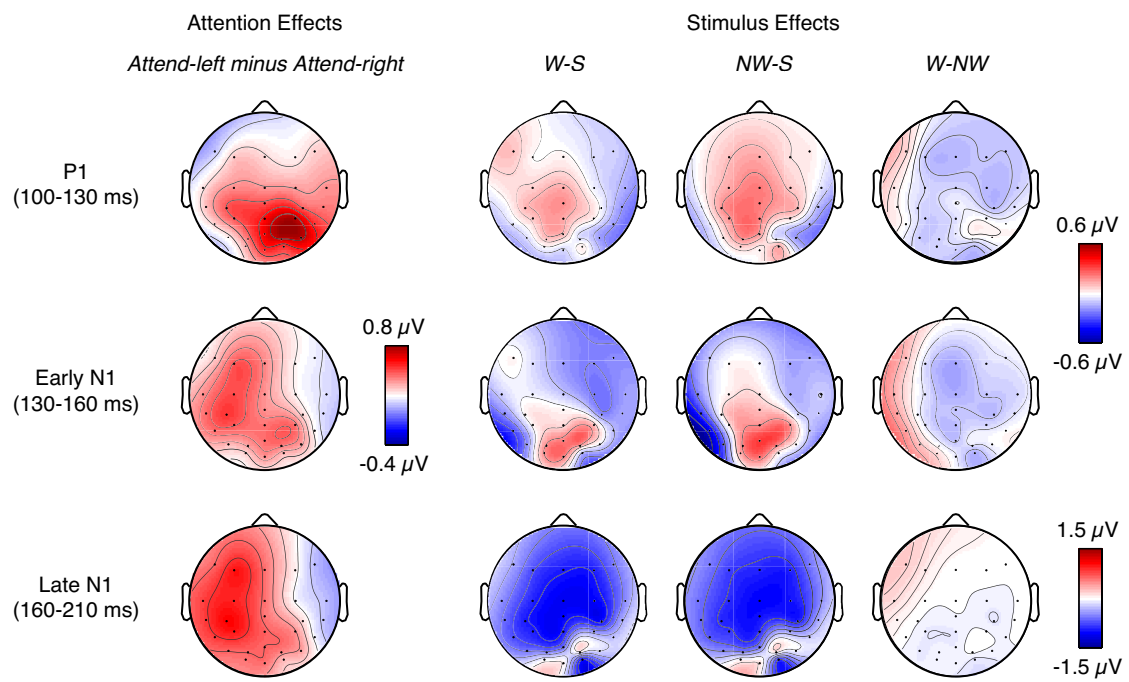


Figure 4-4. Topographic distributions of attention effects and stimulus effects during P1, early N1, and late N1 latency ranges in Experiment 3. Data for the three kinds of stimulus were collapsed for attention effects, and data for the attend-left and attend-right conditions were collapsed for stimulus effects. W-S: word minus symbol. NW-S: nonword minus symbol. W-NW: word minus nonword.

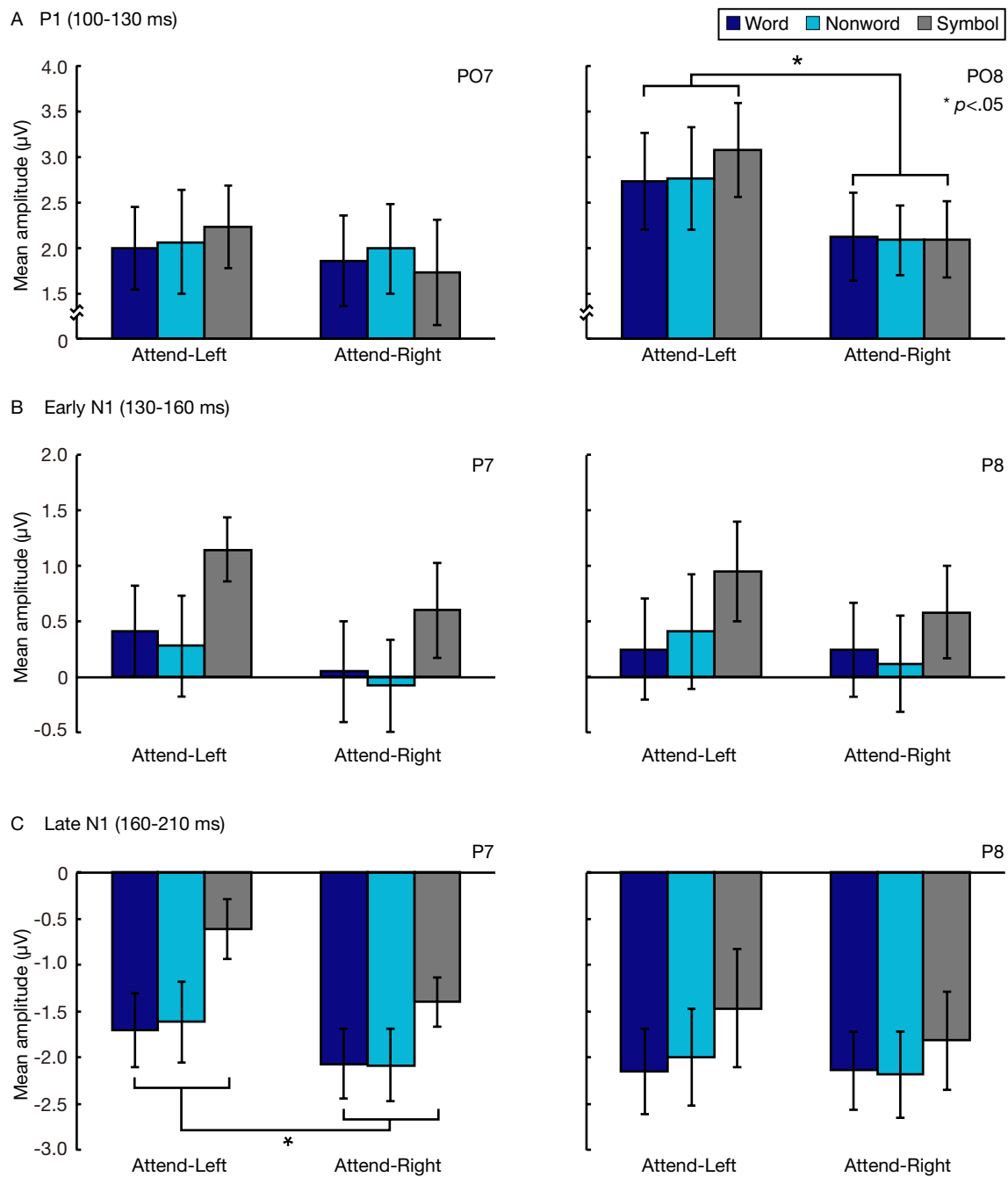


Figure 4-5. Mean amplitudes of ERPs for standard stimuli during P1, early N1, and late N1 latency ranges in Experiment 3.

(A) Mean amplitude of P1 (100-130 ms) at occipito temporal electrodes (PO7, PO8). (B) Mean amplitude of early N1 (130-160 ms) at P7, P8. (C) Mean amplitude of late N1 (160-210 ms) at P7, P8. Error bars indicate the standard errors of the mean.

4.4. Discussion

This experiment aimed to explore whether the bilateral print-tuned N170 in response to Hiragana strings occurs based on integrated letter-string percepts, by using lateralized spatial attention effects in early visual ERPs as an index of perceptual integration. As a result, a bilateral print-tuned N170 was observed in early and late N1 latency ranges (130-160 ms and 160-210 ms, respectively), consistent with Experiment 1 and the sparse condition in Experiment 2. Spatial attention effects were observed as enhancements of the amplitudes of P1 (100-130 ms) at the right occipito-temporal site and late N1 (160-210 ms) at the left occipito-temporal site contralateral to attended hemifields. These attention effects occurred regardless of Hiragana or symbol strings.

4.4.1. *Perceptual units for the bilateral print-tuned N170*

The present spatial attention effect in late N1, although limited to the left hemisphere, was found similarly with those for separate stimuli (Kasai, 2010; Kasai & Takeya, 2012), when contrasted to positive or around zero N1 attention effects for connected stimuli in those studies. While bilateral stimuli consist of letters and unfilled lines has been shown to lack N1 attention effect (Heinze et al., 1990; Kasai, Takeya, & Tanaka, 2014; Luck, Heinze, Mangun, & Hillyard, 1990), letters and symbols used in the present study were overall more complex than those, and many of them, if not all, had more than one closed lines. Thus, they could have been processed as objects that contain surfaces, the selection of which has been linked to the lateralized N1 attention effect (Kasai et al., 2014). Therefore, the present N1 attention may be associated with the selection of a letter or a symbol at the attended location, which did not indicate

attention-spreading effect for Hiragana strings against symbol strings.

The present N1 attention effect suggests that the extent to which Hiragana strings were grouped should not differ from symbol strings. Since the symbol strings should have not been learned to process as a group, the result suggests that Hiragana strings with wide interletter spacing were represented as separate letters at this time, rather than as unitary letter strings. According to the suggestion based on the N1 attention effect, the bilateral N170 specialization observed in this experiment may be associated with the processing of, or underlying representations of, separate Hiragana letters. This interpretation is consistent with the fact that single alphabetic letters elicit bilaterally enhanced N170 compared to control stimuli (Stevens et al., 2013), or with that widely-spaced letters, similar to those used in this experiment, induce letter-by-letter processing (Cohen et al., 2008; Risko et al., 2010, 2011). Therefore, the N170 specialization for letter strings may not necessarily occur at a level of integrated strings as it has been generally assumed (Maurer et al., 2005a). Moreover, it implies that Hiragana strings do not obligatorily have integrated representations upon visual contact with them, but require certain conditions in expert adult readers.

In the three experiments of this study, the conditions under which the Hiragana strings elicited bilateral N170 enhancements may share one thing in common: they were not entirely covered by spatial attention. In Experiments 1 and 3, the tasks should have disrupted participants from attending to entire Hiragana strings, and the wide interletter spacing may have caused them to exceed the scope of attention in Experiment 2. One possible explanation is that the processing or representation of letter strings may remain

at the level of separate letters, unless an entire letter string is registered within the same spatial focus of attention. In other words, integrated letter-string percepts may not be computed automatically upon print input, but depend on visual attentional operations that integrate features into unitary percepts (Treisman & Gelade, 1980).

As an additional finding, the present bilateral N170 specialization appeared prior to the N1 attention effect, and they did not interact with each other. These results suggest that Hiragana-letter percepts can be constructed irrespective of attentional operations reflected in the N1 spatial attention effect. The fact that similar bilateral N170 specialization was found for task-irrelevant, or ignored, Hiragana strings in Experiment 1 also supports this notion. This observation raises a possibility that Hiragana letters are represented by base grouping; a preattentive grouping process that is achieved by tuning of individual neurons to specific visual feature conjunctions (Roelfsema, 2006; Roelfsema & Houtkamp, 2011). Hiragana letters consist of relatively simple visual features and feature conjunctions, which most likely distinguish one letter from another. For example, “い” and “こ” both consist of two line segments, and can be distinguished by the orientation of the lines. It may be possible that through extensive reading experience, neurons in early visual areas may gain tuning to visual feature conjunctions that constitute specific Hiragana letters, which might serve as a basis of the bilateral N170 specialization that was identified in this study. This possibility further implies that neural specializations for letter and letter-string processing may involve qualitatively different underlying mechanisms, especially with respect to the engagement of visual attention, which must be clarified in future studies.

4.4.2. *Integration of character strings and behavioral outputs*

While the construction of integrated Hiragana-string representations was not indicated from early-latency ERPs, it may be associated with behavioral outputs. The behavioral performance (hit rate) was worse for words and nonwords than for symbols in the attend-left condition, which indicates less efficient target feature detection at attended spatial location in Hiragana strings. According to previous studies, it may reflect the fact that attention spread over Hiragana strings and led to a decrease in attentional resources to detect a target feature (i.e., two horizontal lines) at the attended location, as with physically connected objects (Kasai, 2010; Kasai & Takeya, 2012; Richard, Lee, & Vecera, 2008). Therefore, the behavioral result may suggest that Hiragana strings that are initially represented as separate letters could become unitary percepts in later processing stages and affect feature selection processes at the attended location. Such late integration processes may be reflected in target N2 (Kasai & Takeya, 2012), which was not analyzed in the present experiment due to an insufficient number of epochs to be averaged.

The behavioral object-based attention effect for Hiragana strings may also be associated with early spatial attention effects. The N1 attention effect was observed only in the left hemisphere, which indicates that selection of an element at the task-relevant location was more prominent in the attend-right condition. This may have caused a ceiling effect in the attend-right condition, as reflected by faster RTs and higher overall hit rates, and negated the effect of object-based attention spreading based on integrated Hiragana-string percepts. This interpretation is consistent with the notion that feature

selection processes at the attended location depend on earlier spatial attention (Anllo-Vento & Hillyard, 1996; Hillyard & Anllo-Vento, 1998; Hillyard & Münte, 1984), and may account for the absence of the behavioral object-based attention effect in the attend-right condition. In summary, the selection of local features within Hiragana strings may depend on both early spatial selection and the later integration of whole letter strings.

4.5. Conclusion

The results of Experiment 3 suggest that attending to a part of widely-spaced Hiragana strings initially leads to the representation of separate letters in early phases of processing, which may later be integrated into a letter-string percept. The bilateral N170 specialization was suggested to occur based on the representation of separate letters that might be coded by preattentive base grouping. The findings in Experiment 3, together with those in Experiments 1 and 2, suggest that Hiragana strings do not necessarily have obligatory integrated representations, unless subserved by visual attention. Since this notion is may be related to the possibility that impaired reading in developmental dyslexia stems from visual attention deficits that disrupt the orthographic encoding of letter strings (Vidyasagar & Pammer, 2010), further examinations are necessary to clarify their precise relationship.

5. General Discussion

5.1. Summary of the Experimental Findings

The present study consisted of three experiments to investigate the early stages of Hiragana string processing reflected in the print-tuned N170. Figure 5-1 shows the overview of the experimental findings. Experiment 1 identified the fast perceptual categorization process in Hiragana script under the restriction of linguistic processing. Rapidly presented and task-irrelevant Hiragana strings elicited larger N1 than symbols, consistent with the N170 print-tuning that has been found in other languages (alphabetic: Bentin et al., 1999; Maurer et al., 2008; Simon et al., 2004. Chinese: Lin et al., 2011; Wong et al., 2005). However, the print-tuned N1 in Experiment 1 was bilateral as opposed to the typical left-lateralized N170 in expert readers (Bentin et al., 1999; Mahé et al., 2012; Maurer et al., 2005a; Simon et al., 2004), including those in Hiragana script (Horie, et al., 2012; Maurer et al., 2008). Therefore, the results suggested that while fast perceptual categorization processes operate largely independent of linguistic processing, other early processes could be affected by the rapid stimulus presentation and/or ignorance of letter strings.

Experiment 2 found that the early phonological mapping process in a transparent script requires attention to print stimuli themselves. With the same stimuli and presentation conditions as in Experiment 1, Hiragana strings elicited left-lateralized N170 when they were involved in a task. In addition, this N170 left-lateralization was observed only when constituent letters are closely located, or when the parallel application of attention to the letters is possible (Cohen et al., 2008; Risko et al., 2010,

2011). Furthermore, Experiment 2 identified very early neural specialization for words that might be associated with more efficient feature processing for words compared to symbols. Taken together, the results of Experiment 2 suggested that object-based attention mechanisms play a role in very early visual processing and relatively early phonological mapping in Hiragana script.

The results of Experiments 1 and 2 suggested the existence of two kinds of print-tuned N170 in response to Hiragana strings; i.e., the bilateral and left-lateralized print-tuned N170. While the left-lateralized N170 was suggested to involve grouped letters, the bilateral N170 was observed for Hiragana strings that may be difficult to integrate into a unified percept (i.e., unattended and/or widely spaced). This raised the question of whether bilateral N170 specialization occurs based on representations of separate Hiragana letters or unitary percepts of Hiragana strings, which was examined in Experiment 3.

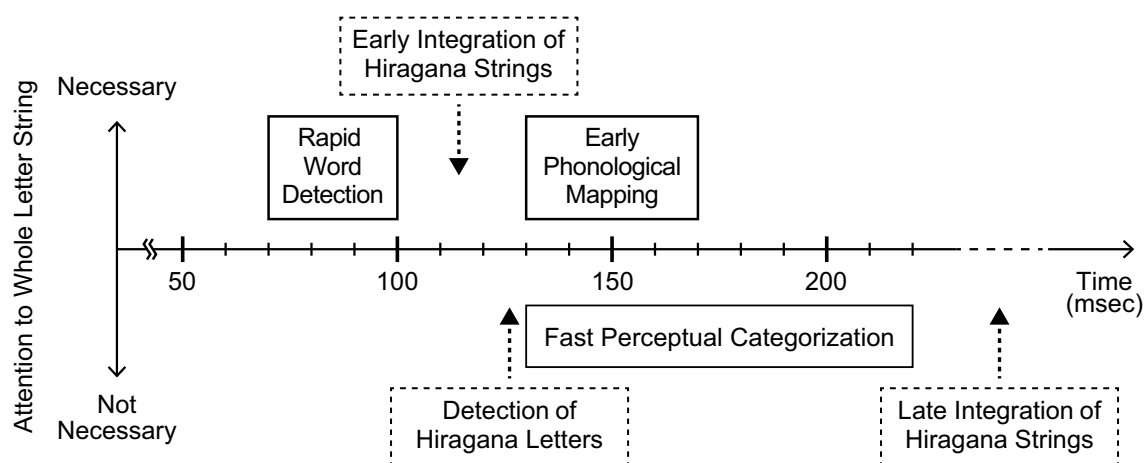


Figure 5-1. Time course and involvement of attention in early processes related to print-tuned N170 in response to Hiragana strings.

Experiment 3 showed that bilateral N170 specialization for Hiragana strings may occur based on representations of separate letters. In this experiment, participants directed their attention to a location within widely-spaced Hiragana and symbol strings (i.e., sparse condition in Experiments 1 and 2) and detected a local visual feature at that location. As a result, a lateralized N1 spatial attention effect was observed equally for Hiragana and symbol strings, which suggested that Hiragana strings had not yet had integrated representations in this time window. In addition, the N170 specialization for Hiragana letters was shown to precede attentional selection of them, which suggested that Hiragana letters may be coded preattentively as base groupings (Roelfsema & Houtkamp, 2011). Lastly, decreased target detection for Hiragana words and nonwords in behavioral performances indicated that Hiragana strings could become unitary percepts in later stages.

5.2. Hiragana String Processing under Rapid Stimulus Presentation

To resemble the conditions in normal reading, all experiments in the present study used rapid stimulus presentation to reduce the attentional resources that are available for each stimulus. Based on the experimental findings, this section will present a possible explanation for the early stages of Hiragana string processing in expert adult Japanese readers.

5.2.1. *Early perceptual processing of Hiragana letters*

All three experiments demonstrated the existence of a fast neural mechanism to classify print inputs as representing Hiragana letters, which was reflected in the early

bilateral print-tuned N170. This may be consistent with the print specialization that exists at the level of single letters in other scripts (Stevens et al., 2013; Wong et al., 2005). As a major finding of the study, this mechanism was shown to operate irrespective of spatial attention. In the experiments, regardless of how spatial attention may be deployed on Hiragana strings (Experiments 2 and 3), and even when attention is not directed to them (Experiment 1), Hiragana strings were distinguished from symbols within 200 ms after presentation. According to the general view of visual word processing (Coltheart et al., 2001), fragmented pieces of print inputs (i.e., visual features and line segments) must be integrated into letters in order for the above-mentioned neural mechanism to operate. However, present results suggested that Hiragana letters may be detected without going through such integration processes.

As discussed in Experiment 3, Hiragana letters may possibly be represented as base groupings; i.e., feature conjunctions whose neural coding depends on the tuning of individual neurons (Roelfsema, 2006; Roelfsema & Houtkamp, 2011). Hiragana letters consist of simple line segments and curves, which could be coded by neurons at relatively lower levels of visual hierarchy, where a larger number of base groupings may be available (Roelfsema, 2006). In addition, since most Hiragana letters are distinctive at the level of feature conjunction, base groupings should greatly benefit their rapid detection. Furthermore, Hiragana letters appear in Japanese texts not only as a part of words, but also in isolation (e.g., as postpositional particles and suffixes of Kanji words). Due to these characteristics, extensive experience in reading Hiragana

script may increase the tuning of neurons in early visual areas to individual letters and enable the rapid detection of letters as groups. The fast perceptual categorization of Hiragana letters could be associated with this highly efficient perceptual mechanism to attain the critical first step of expert visual word processing; i.e., moving from visual feature units to letter units (Coltheart et al., 2001).

5.2.2. *Rapid Neural Specialization for Hiragana Words*

Experiment 2 revealed that Hiragana string processing under rapid stimulus presentation may involve a very early neural specialization for words that appears prior to the fast perceptual categorization. Hiragana words were differentiated from symbols with extraordinary speed (i.e., within 100 ms), which was observed in an occipital visual ERP component that presumably reflects neural activities in primary visual areas (e.g., Jeffereys & Axford, 1972). This result suggests the existence of neural tuning for Hiragana words in the extremely early stage of visual cortical processing.

This rapid specialization for words may support a model of visual perceptual learning called the Reverse Hierarchy Theory (Ahissar & Hochstein, 2004). It asserts that perceptual learning induces tuning of the visual system that starts at higher levels/areas and propagates to lower levels/areas as the viewer gains expertise in a trained domain. This leads to the increased weighting of informative inputs in higher as well as lower levels/areas, and thus results in the tuning of bottom-up processes. Reading is definitely a form of perceptual learning, and the well-known print specialization in higher visual areas (e.g., VWFA) may eventually progress backward to the primary visual areas to gain sensitivity to invariant information about the

appearance of visual words. Such tuning may also be conceptualized as the existence of learning-induced base groupings in the earliest visual areas (Roelfsema & Houtkamp, 2011) that contribute to the rapid coding of feature conjunctions that represent Hiragana words.

Interestingly, this early word specialization appears to be implemented through increased visual sensory processing. The absence of this specialization in Experiment 1 suggested that this rapid word coding may be based on the facilitation of sensory processing for objects (i.e., words) via object-based attention mechanisms. Indeed, attention to the visual/orthographic properties of words has been shown to increase the early sensory processing of letters (Proverbio & Adorni, 2009). Rapid stimulus presentation may be another possible factor in the implementation of this rapid word specialization. An increase in the stimulus presentation rate has been shown to increase activities in brain regions associated with the analysis of print stimuli, such as the posterior fusiform gyrus (Price, Moore, & Frackowiak, 1996). Although these possibilities will require further examinations, attention and a high input rate may contribute to maximization of neural signals related to the early sensory processing of words.

In summary, the present study suggested the existence of an extremely fast word-detection mechanism in the initial phase of Hiragana string processing. It may be learning-induced, and its implementation may depend on the extent of early sensory processing. Since attention to letters and a high input rate both constitute normal

reading in experts, such a mechanism should contribute to their remarkable fluency.

5.2.3. *Early phonological mapping*

The contrast between Experiments 1 and 2 indicated that the early phonological mapping with Hiragana script requires not only the visual contact with print stimuli but also the direction of visual attention to them. In addition, Experiment 2 suggested that phonological mapping is more pronounced for grouped Hiragana strings. These findings were interpreted in terms of object-based attention, in that attending to a feature of print facilitates the processing of all of its properties, including phonological information. In summary, Hiragana string processing under rapid stimulus presentation was suggested to involve early phonological mapping processes at the level of whole strings, in which visual attention acts as a trigger for the activation of phonological information.

Regarding the neural mechanisms that underlie this early phonological mapping, the Interactive Account of the ventral occipitotemporal cortex (vOT) by Price & Devlin (2011) may provide a reasonable framework. This account proposes that the perception of visual words involves bottom-up sensory inputs from visual areas and top-down predictive inputs from phonological and semantic processing areas, with the vOT as their interface. The top-down inputs are learning-dependent and are considered to engage in a non-strategic manner when words are presented visually. Based on this account, the early phonological mapping processes reflected in the left-lateralized N170 may involve such predictive signals from phonological areas that influence the visual/orthographic analysis of print in the VWFA, a portion of the left vOT (McCandliss et al., 2003). Moreover, although speculative, the activation of phonology

via object-based attention mechanisms could be regarded as an increase in such top-down signals due to enhanced neural representations of letter strings.

Importantly, this account also asserts that bottom-up inputs of visual information accumulated in the vOT must be sufficiently specific to induce activation in phonological areas to generate top-down signals (Price & Devlin, 2011). In this regard, spatial attention to whole Hiragana strings, as in the dense condition of Experiment 2, would amplify their sensory signals in the visual pathway (for a review, see Hillyard & Anllo-Vento, 1998). Moreover, the act of attending to an object has been shown to enhance neural activities in the category-specific area for that object; e.g., attending to faces and houses increases activities in the fusiform face area and the parahippocampal place area, respectively (Baldauf & Desimone, 2014; O’Craven, Downing, & Kanwisher, 1999). Regarding the print-tuned activation of the VWFA, a higher level of attention has been suggested to increase the strength of a category-specific neural signal (Xu, Jiang, Ma, Yang, & Weng, 2012). Based on above evidence, spatial attention to print would increase the specificity of its representations accumulated in the vOT, or VWFA, which might induce increased top-down inputs from the phonological area that may underlie early phonological mapping processes.

5.3. Early Stages of Hiragana String Processing: Overview and Model

Figure 5-2 illustrates a putative model for the early stages of Hiragana string processing in expert adult Japanese readers based on the present findings. The early stages of expert Hiragana string processing were suggested to involve specializations in

the processing of single letters, whole letter strings, and phonological mapping. On the whole, they were similar to previous findings in other languages. However, the present study found that the processing of separate letters and that of whole letter strings may be different in terms of their requirements for spatial attention. The processing of letters was suggested to operate independent of spatial attention, so that it may largely be dependent on input-driven activations of specialized neural circuits developed through reading experience. On the other hand, the processing of letter strings seems to require spatial attention that covers whole strings in order for the above-mentioned specializations to come fully into effect. This proposition is consistent with the well-established Feature-Integration Theory of Attention (Treisman & Gelade, 1980), which predicts that constituent letters may be integrated into a unitary percept only when they are registered within the same spatial focus of attention. This integrated percept may be a critical basis of the specialization at a level of whole strings, as has been proposed for alphabetic languages (McCandliss, et al., 2003). Thus, in letter-string processing, while specialized neural circuits seem to exist as its devices, visual attention may serve as a switch to turn them on. To conclude, while extensive reading experience develops reading-related expertise, spatial attention may be critical for implementing such expertise in visual word processing.

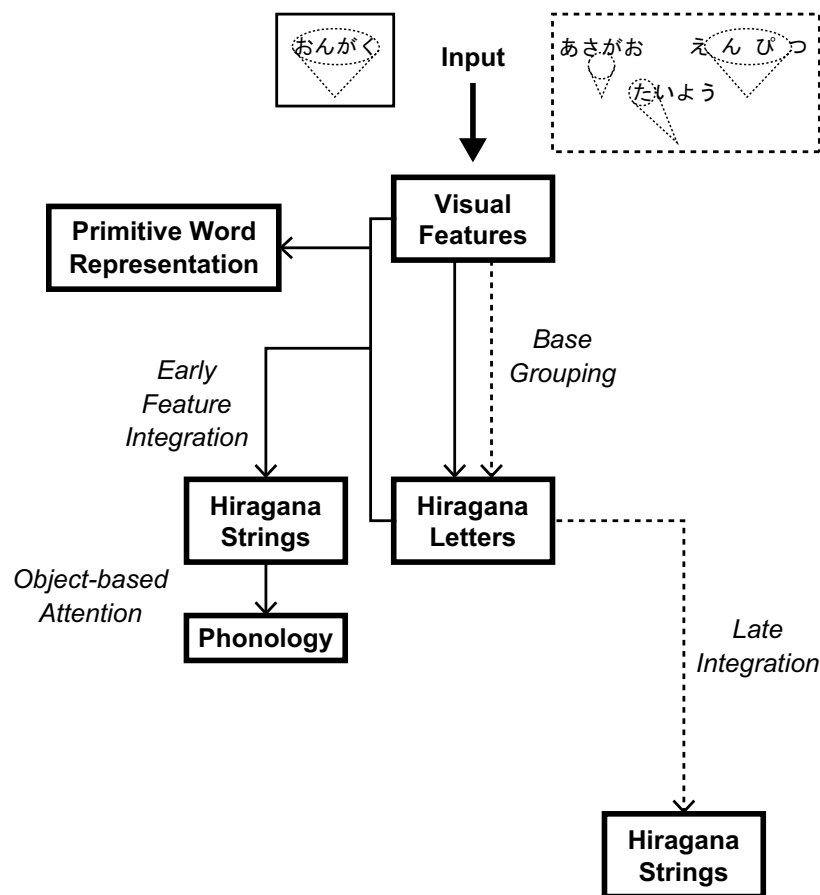


Figure 5-2. A putative model of early Hiragana string processing.

Each box represents the content of neural representation at that stage. Arrows in solid lines show the course of processing for Hiragana strings covered by spatial attention, while those in dashed lines show the course for those that are not registered entirely within a spatial focus of attention. Possible underlying mechanisms of each process are indicated in italics.

5.4. Issues for Future Research

5.4.1. *Cross-linguistic comparisons*

Although visual word processing has been shown to generally involve common brain regions (Bolger, Perfetti, & Schneider, 2005), different languages have different requirements for reading. Therefore, an examination of the present findings in different languages is crucial for the further clarification of early print processing. For example,

while Hiragana letters could be represented as base groupings (Roelfsema, 2006; Roelfsema & Houtkamp, 2011), the situation may be different in other scripts like kanji and alphabets. Kanji script is more complex than Hiragana, and consists of multiple feature conjunctions (i.e., radicals) that are often shared among multiple Kanji. Lower-case alphabets share similar feature conjunctions among many letters (e.g., p, q, b, d). In these scripts, base groupings may not be suited for rapid letter/character identification, and thus fast neural processes for single letters/characters in those scripts might involve different mechanisms. The rapid specialization for words may also easily be affected by script properties. Early visual areas by their very nature represent more local visual information, and the specialization of these areas for print may be limited to scripts like Hiragana, in which smaller units (i.e., single letters) can individually serve as a unit of subsequent reading-related processes like phonological processing.

Regarding phonological mapping, the transparency of a script is known to affect its automaticity (Maurer et al., 2005a, 2005b; Zevin & Balota, 2000). Therefore, different languages may have different requirements for the triggering of phonological processes. In Hiragana script, attending merely to a simple surface feature (i.e., color) was suggested to activate phonological information via object-based attention mechanisms. This may be possible because Hiragana letters are associated with distinct sounds very intimately in a one-to-one manner. In opaque scripts like English, letter-to-sound conversion is more complex and may require a higher level of attention. Conversely, if visual word processing involves phonology in a universal manner (Frost, 1998), early

phonological mapping may share a common underlying mechanism and has the same requirements across different languages.

As described above, different languages have different properties that may or may not affect early stages of print processing. Clarification of the commonalities and differences among them should contribute to a further understanding of how the human brain, or information processing system, adapts to the requirements for reading.

5.4.2. *Course of development*

The present study examined Hiragana string processing in expert Japanese readers. Since the early processes identified in the study must be the outcomes of extensive reading experience, clarifying the course of their development is necessary for a full understanding of reading-related expertise in early print processing. Developmental changes in print-tuned N170 have been well-studied in German-speaking children. A series of studies revealed that differentiation between visual words and visual control stimuli is almost absent in preschoolers (Maurer et al., 2005b), but becomes apparent after about 1.5 years of reading practice (Maurer et al., 2006). This indicates that the fast perceptual categorization processes come into play early in the course of reading development. The N170 left-lateralization, on the other hand, typically appears much later, such that it is still not seen in children around 10 years old (Kast et al., 2010). This shows that early phonological mapping processes take longer to reach the level in expert adult readers.

Although the present study identified similar processes in expert Hiragana reading, they may not necessarily follow an identical course of development. Especially, in the

process of learning to read Hiragana, a high level of reading accuracy is achieved quite rapidly, which may even be faster than with German. It is possible that reading acquisition in Hiragana script may be associated with the faster development of early processes. For example, the extremely high transparency of Hiragana may result in the earlier development of phonological mapping processes. On the other hand, a developmental study on print-tuned N170 in Chinese kanji suggested that different scripts may share common developmental trajectories regarding print specialization (Cao, Li, Zhao, Lin, & Weng, 2011). Therefore, a necessary complement to this study would be the clarification of both specificity and commonality in the development of early Hiragana processing.

5.5. Implications for Developmental Dyslexia

Developmental dyslexia is a specific learning disability that is characterized by low reading and spelling abilities despite average intellectual abilities, an adequate learning environment, and motivation. As a widely accepted notion, developmental dyslexia is caused by impaired letter-to-sound mapping due to poor phonological awareness (e.g., Ramus et al., 2003). However, there is also evidence that dyslexia is associated with impaired orthographic processing (e.g., Maurer et al., 2007; Savill & Thierry, 2011; Vidyasagar & Pammer, 2010). Findings in the present study regarding early stages of print processing may provide further insight into the cause of developmental dyslexia and provide implications for assessments and interventions.

5.5.1. *Examining orthographic processes via bilateral print-tuned ERP*

The bilateral N170 identified in the present study indicated the existence of the fast perceptual categorization process that is automatically driven by print inputs. Moreover, this process may serve as a basis of other early processes, namely phonological mapping and attentional selection of a single letter, since their relevant ERP effects were found concomitantly with the bilateral N170 enhancement. Therefore, impairments in fast perceptual categorization may affect any subsequent processes in print processing and lead to inefficient reading. In fact, dyslexic adults in alphabetic languages are reported to show reduced print-tuning in early visual processing (Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999; Mahé, Bonnefond, & Daignon-Camus, 2013; Mahé et al., 2012; Salmelin, Kiesilä, Uutela, & Salonen, 1996), which suggests a link between impaired reading and failure in the fast perceptual categorization of print. As a topic for future studies, an examination of the bilateral print-tuned N170 in Japanese dyslexics should be important for clarifying whether their reading difficulties originate from abnormalities in early perceptual processes. Such an examination may also reveal whether fast perceptual categorization is a critical first step in the fluent reading of Hiragana strings.

Moreover, the bilateral print-tuned N170 response could be used as an index to assess orthographic coding in dyslexics separately from phonological deficits. Previous studies have found a lack of left N170 print-tuning in adult dyslexics, which was linked to an impaired visual expertise for print (Mahé et al., 2012, 2013). However, since the left-lateralized N170 may involve both orthographic and phonological processes

(Maurer & McCandliss, 2007), we can not rule out the possibility that the impaired left N170 specialization reflects deficits in not only orthographic coding but also phonological mapping. This problem has also been pointed out regarding reduced print-tuned activities in the left occipito-temporal region in developmental dyslexia (Kronsnabel et al., 2013). Use of the bilateral print-tuned N170 response may eliminate such confounding in the assessment of early orthographic processes, since it is minimally affected by other processes. This newly identified ERP component may be used to disentangle the complex interrelation of multiple processes in early print processing, and to further clarify orthographic coding deficits in developmental dyslexia.

5.5.2. *Visual attention deficits may impede access to phonology*

Early phonological mapping based on object-based attention mechanisms implies that impaired letter-to-sound mapping in dyslexia could arise from both phonological deficits and visual attention deficits. If dyslexics have impaired phonological representations in the first place, attention to print could not trigger phonological mapping. However, even if they have intact phonological representations, the early phonological mapping processes should be hindered if they are unable to cover print with attention. This latter causality is in line with the visual deficit account of developmental dyslexia (Vidyasagar & Pammer, 2010). Children with developmental dyslexia exhibit dysfunction of visual attention, such as in spatial orientation (Facoetti, Paganoni, & Turatto, 2000; Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012) and the ability to sustain focused attention to visual stimuli (Facoetti et al., 2000). The

visual attention deficit account links such dysfunctions to disruption in the visual encoding of letter strings, which consequently hinders phonological mapping (Vidyasagar & Pammer, 2010). However, our finding implies that deficits in visual attention, i.e., object-based attention, themselves could directly disrupt rapid access to phonological information.

A failure in early phonological mapping could lead to inefficient phonological recording in dyslexics, given a link between N170 left-lateralization and later phonological processing reflected in an N450 rhyming effect (Stevens et al., 2013). Moreover, since early phonological mapping may mediate rapid access to semantic information (e.g., Lesch & Pollatsek, 1993), deficits in it could also hinder reading comprehension. Therefore, even if dyslexics have intact phonological representations, disruptions in mechanisms to access them would cause impaired reading (Boets et al., 2013). Based on the present study, the mechanisms of visual attention may play a critical role in phonological access, and further research on this topic should be fruitful for clarifying the causes of and interventions for the remediation of developmental dyslexia. For instance, a child with impaired phonological mapping may require not only phonological remediation but also interventions to overcome visual attention deficits.

5.5.3. *Connections with the visual attention span deficit hypothesis*

The role of visual attention in reading suggested from the present study may have some relevance to the visual attention span (VA Span) deficit hypothesis of developmental dyslexia proposed by Bosse, Tainturier, & Valdois, (2007). The VA

Span is defined as “the amount of distinct visual elements that can be processed in parallel in a multi-element array” (Bosse et al., 2007, p. 198), and is typically estimated by the number of correctly reported elements in briefly flashed multi-element arrays, such as strings of consonants (i.e., partial and whole report tasks, see Lallier & Valdois, 2012 for details). It is considered to reflect the amount of visual elements to which attention can be allocated simultaneously; thus, a sufficiently large VA Span would be necessary for efficient whole-word processing. Bosse et al. (2007) found worse performance by dyslexic readers in VA Span tasks and strong correlations between task performance and reading ability, which has led to the VA Span deficit (i.e., reduction in the number of letters that can be processed simultaneously) as an alternative cause of a phonological deficit.

While the VA Span hypothesis views visual attention as a function for processing multiple elements in parallel, the present study regarded it as a function to integrate and process letters as unitary objects. Although these two views appear to contradict each other, notions from this study may provide perspectives to further clarify the nature of VA Span. For instance, the processing of letters as a group may enhance the representation of each letter, as reflected by word/pseudoword superiority effects (Chase & Tallal, 1990; Reicher, 1969; Wheeler, 1970). Given this, the successful grouping or integration of elements in early processing stages may underlie the larger VA Span. As a different account, the VA Span may be based on an attentional process called the “individuation” of elements to scrutinize each of them (Intriligator &

Cavanagh, 2001), which should be necessary for reporting elements correctly. Therefore, an exploration of links between attentional operations and functions that modulate early visual processing may further clarify the mechanisms that underlie the VA Span and its deficits, which should lead to a better understanding of impaired reading in developmental dyslexia.

5.6. Concluding Remarks

The present study made two major findings in the early stages of Hiragana string processing. 1) Neural specialization for Hiragana strings arise under rapid stimulus presentation, so that they are very likely to serve as bases of fast and efficient reading. However, 2) there are also processes that operate in coordination with visual attention functions. Since early print processing is generally considered to be automatic, in the sense that it is obligatorily triggered by print inputs, the role of visual attention is a particularly important indication from this study. This finding should help us to elucidate not only the fluent reading in experts, but also the impaired reading in developmental dyslexia.

6. References

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