Multisensory learning with haptic reading plates improved RAN（Rapid Automatized Naming）, reading and writing skills

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The aim of this study is to investigate the impact of multisensory learning with haptic resources on school-aged children in Japan. The three-dimensional Japanese phonogram（kana）designed for haptic learning were used in this study. 8 children with developmental reading and writing difficulties and difficulties with RAN（Rapid Automatized Naming）tasks have completed multisensory learning using these Japanese kana. Haptic reading learning was conducted by following the sequence of basic characters composed of kana, irregular mora characters, single words, and short sentences, while watching, touching, and reading the materials aloud. The study showed the positive impact of multisensory learning on the RAN subtest in STRAW-R in 7 out of 8 students post-learning. Also, the scores in reading fluency improved in 7out of 8 students with reading difficulties, as did the scores in the Kana writing task in 4 out of 4 children with writing difficulties. The questionnaire completed post-study revealed a reduced effort on reading and writing. Reading training with active touch improved the letter and word shape memory and formation of associative memory between letters and sounds through haptic exposure. However, it does not explain the increased score in the RAN task, as numbers and pictures, which are stimuli of RAN tasks, were not included in our learning task.The improvement in letter shape memory through haptic learning may have functioned as a cognitive cue within working memory, facilitating the recall of phonological information.

Introduction

It is known that some children show significant difficulties in reading and writing, despite having no delays in overall intellectual development and no impairments in sensory functions such as vision or hearing. In the fields of medicine and education, these children are defined as having developmental dyslexia. These children are known to have difficulties in reading fluently, as well as in acquiring new letters and expressing themselves through writing. Among the causes of specific reading and writing difficulties, reading problems are often related to weaknesses in phonological processing. Underlying these difficulties is a reduced ability to decode the correspondence between letters and their sounds. Furthermore, a weakness in visually recognizing groups of letters as whole word forms also contributes to difficulties in fluent reading. Neurological studies have also reported findings on the neural basis of developmental dyslexia. The decoding of letter–sound correspondences is primarily carried out by the left temporoparietal region, with the left inferior frontal gyrus playing a supportive role. Additionally, the visual recognition of word forms has been shown to involve the left fusiform gyrus [2]. Reading while having weaknesses in reading-related functions can lead to cognitive fatigue (mental exhaustion), which may cause children to avoid reading and can negatively affect their motivation to learn [3]. Regarding writing, weaknesses in visual information processing—such as visual perception and visual memory—are believed to affect the acquisition and written expression of complex character forms, particularly kanji [4]. A study by Uno et al. [5] investigating the cognitive functions underlying reading and writing difficulties in children reported that not only phonological processing, but also visual perception and Rapid Automatized Naming (RAN), are involved in a complex manner. In particular, the speed of RAN tasks—such as naming pictures and numbers alternately before school entry—has been shown to be a highly accurate predictor of later reading difficulties after school entry [6]. As developmental dyslexia is influenced by various cognitive factors, two main instructional approaches have been implemented in Japan. For improving reading skills, decoding instruction that emphasizes oral reading practice has been employed [7]. This approach begins with teaching the correspondence between letters and their sounds, and then gradually progresses to enhancing word form recognition so that words can be read as whole units. Improvements in reading fluency have been reported through this method. An international study that investigated changes in brain function following similar decoding training [8] reported not only compensatory functional improvements, but also changes in brain activity patterns that more closely resemble those of typically developing children. For children who struggle with acquiring complex characters such as kanji, the "bypass method" (auditory approach)—which focuses on utilizing their preserved auditory verbal memory to encode the structure and meaning of kanji verbally—has also been reported to be effective [9]. In other countries, multisensory learning that incorporates active tactile perception (active touch) has been used to support children with reading and writing difficulties. One example includes the use of clay modeling of alphabet letters, which has been shown to be effective [10]. Such haptic-based learning approaches have been applied not only to children with dyslexia, but also to preschool children who have not yet acquired literacy skills. A study conducted in France [11] found that, in a task involving learning the spelling and pronunciation of words, children who engaged in tactile exploration of three-dimensional letters performed better on decoding tasks assessing letter–sound correspondences than those who used visual exploration alone. The study concluded that tactile exploration helped young children better understand the correspondence between letters and sounds, and was effective in strengthening the connection between visual and phonological representations. In the context of letter learning, academic rationale for utilizing active haptic perception includes the enhancement of attention through haptic feedback and the benefits of dual coding by integrating multiple sensory modalities. In a memory experiment using a three-dimensional version of the Rey-Osterrieth Complex Figure [12], it was reported that combining visual input with haptic interaction helped direct attention to the structural features of the figure, resulting in improved performance in drawing-based recall tasks. Furthermore, a physiological study [13] has reported that multimodal image formation occurs through shared neural substrates across the lateral occipital complex (LOC), fusiform gyrus (FG), and precuneus, which are activated in both visual and haptic modalities. This suggests that physically confirming a visual object through haptic interaction can enhance cross-modal memory traces, thereby reinforcing learning through integrated sensory processing. Multisensory learning methods that incorporate active haptic perception have typically been applied to both typically developing children and those with dyslexia, mainly for the purpose of teaching unfamiliar letters. However, there have been few prior attempts to use such methods specifically to enhance reading fluency or to improve orthographic recall during writing. In response, we developed a multisensory learning approach in which learners "look, touch, and read aloud" using raised letter plates produced by a 3D printer. We hypothesized that for children with reading and writing difficulties, engaging in haptic reading—decoding practice involving reading aloud while touching raised letters—would allow tactile input from the fingertips to function as a cognitive cue. This, in turn, may facilitate more effective formation of letter-shape memory, letter–sound associative memory, and enhanced word-form recognition. To examine the validity of this hypothesis prior to conducting a controlled trial, we conducted a pilot study involving eight children with reading and writing difficulties.

Ⅰ. Methods

1. Participants

The participants in this study were eight upper elementary school children who had no visual or auditory impairments but showed significant difficulties in reading and writing Japanese kana characters. Their mean age was 10.4 years (range: 9.3–12.4 years). The inclusion criteria were being in the upper grades of elementary school and having observable difficulties in kana literacy. Among the eight participants, five had been medically diagnosed with learning disabilities (LD), and two of them were also diagnosed with comorbid developmental disorders such as ADHD or ASD. The remaining three participants had not received a formal diagnosis; however, both the children and their caregivers reported notable difficulties in reading and writing. In addition, a clear discrepancy between their intelligence test scores and reading/writing performance (as described later) suggested characteristics consistent with developmental dyslexia. The children's kana reading and writing abilities were assessed using the Revised Standardized Test for Reading and Writing (STRAW-R). To eliminate the effects of age differences, all scores were converted to z-scores for analysis. For the rapid reading task, the time required (in seconds) to read five items—hiragana words, hiragana non-words, katakana words, katakana non-words, and sentences—was used as an index of reading fluency. For the dictation (listening-to-writing) task, participants were asked to write down 20 kana characters (10 hiragana and 10 katakana) that were presented orally. The number of correctly written characters was used to evaluate kana writing output ability. According to the STRAW-R test manual [14], a z-score of +1.5 or higher in the rapid reading task is recommended as a cutoff for identifying reduced reading fluency, while a z-score of −1.5 or lower in the dictation task is recommended as a cutoff for identifying reduced writing accuracy. In this study, we adopted the same criteria: z-scores of +1.5 or higher for reading time and −1.5 or lower for correct responses in the writing task were used as cutoff thresholds for identifying functional impairments. Based on the STRAW-R test results, the eight children's reading and writing abilities were classified into two categories: reading difficulties and writing difficulties. If a child showed difficulties in either the hiragana or katakana dictation (listening-to-writing) task, they were categorized as having writing difficulties. According to the STRAW-R test manual [14], if a child shows a z-score of +1.5 or higher in reading time or error responses in even one of the five rapid reading tasks, there is a 92.89% likelihood that they meet the diagnostic criteria for developmental dyslexia related to reading problems. In this study, we adopted the same criterion: any child who exhibited a delay in reading time exceeding the cutoff (z ≥ +1.5) in at least one of the five rapid reading tasks was classified as having reading difficulties. All eight children exhibited symptoms of reading difficulties, and four of them (Cases 2, 3, 6, and 7) also demonstrated writing difficulties. The profiles of reading and writing difficulties for each participant are summarized in Table 1.

Table 1. Profiles of Eight Children and Their Pre-Haptic Reading Performance on RAN, STRAW-R Speed Reading, and Dictation Tasks

Dyslexia Cases				STRAW-R (Reading and Writing Achievement Levels)							
				Naming Speed	Reading Fluency					Auditory Writing	
No.	Grade	Gender	Classification	RAN	Hiragana Word	Hiragana Non-word	Katakana Word	Katakana Non-word	Passage	Hiragana	Katakana
1	4	Male	Reading	9.3*	9.5*	4.5*	8.2*	3.7*	2.1*	-1.3	0.0
2	4	Male	Reading & Writing	2.2*	1.6*	0.2	0.7	0.5	0.0	-8.0*	-3.5*
3	6	Male	Reading & Writing	3.5*	7.6*	5.3*	7.6*	3.8*	4.9*	-3.0*	-0.4
4	4	Male	Reading	4.0*	3.2*	4.0*	5.4*	2.9*	1.9*	0.3	0.0
5	5	Male	Reading	4.5*	4.4*	4.7*	4.0*	4.1*	1.9*	-1.3	-0.7
6	6	Female	Reading & Writing	2.1*	0.4	2.5*	0.4	1.6*	2.0*	0.3	-4.7*
7	5	Male	Reading & Writing	4.2*	11.7*	3.4*	11.4*	4.6*	16.4*	-1.3	-6.9*
8	4	Male	Reading	2.2*	0.9	1.6*	-0.1	0.2	0.2	0.3	0.0

A cutoff value of z = ±1.5 was used to identify areas of difficulty, which were marked with an asterisk (*). For the RAN and speed reading tasks, items requiring z-scores of 1.5 or higher in processing time were considered difficult. For the writing-to-dictation task, items with z-scores of –1.5 or lower in accuracy were considered difficult.

To assess the participants' general intellectual ability, the Raven's Coloured Progressive Matrices (RCPM) was administered. The RCPM has been reported to have a high correlation with the WISC and is commonly used as a screening tool for evaluating intellectual functioning in children with reading and writing disorders [15]. The RCPM consists of three subtests. The average total score among the eight participants was 34 points, with a mean z-score of 0.5. No child scored below a z-score of 1.0. All participants were confirmed to have intellectual abilities within the average range. A previous study on children with reading and writing difficulties [5] reported that multiple underlying cognitive weaknesses often coexist. In the present study, we also assessed background cognitive functions using the same evaluation tasks and cutoff criteria (z-score ±1.5) as in the previous research. Based on the assessment results, participants were categorized according to combinations of deficits in Rapid Automatized Naming (R), Visual Cognitive Function (V), and Phonological Function (P). To evaluate rapid automatized naming ability, we used the RAN subtest of the STRAW-R, which measures the speed at which participants alternately name pictures and numbers. Children who scored a z-score of +1.5 or higher in the average total time across the three RAN tasks were classified as having difficulties in rapid automatized naming (RAN). Visual cognitive function was assessed using the Rey-Osterrieth Complex Figure Test (ROCFT), which included a copy task as well as delayed recall tasks administered 3 minutes and 30 minutes later [16]. Phonological awareness was evaluated using a task consisting of repetition and backward repetition of four-mora non-words [17]. For both assessments, z-scores were calculated based on normative data from over 50 typically developing children per grade level. Children with a z-score of −1.5 or lower were classified as having difficulties in the corresponding cognitive domain. All eight participants showed deficits in rapid automatized naming (R). Deficits in visual cognitive function (V) were observed in Cases 5 and 8, while phonological awareness (P) deficits were identified in Cases 3, 4, and 8. The intellectual levels and cognitive function profiles of these children are summarized in Table 2.

Table 2. Evaluation of Background Cognitive Functions and Classification of Types in Eight Children

Dyslexia Cases		Intellectual levels	Naming Speed	ROCFT (Visual Cognitive Function)			Phonological Awareness	
No.	Classification	RCPM	RAN	Copying	Recall (3-mi)	Recall (30-mi)	4-Mora Word	4-Mora Non-word
1	R	0.2	9.3*	0.9	-0.5	-0.1	-0.1	-0.5
2	R	0.6	2.2*	1.3	0.5	1.2	-0.1	0.5
3	PR	0.8	3.5*	0.7	-0.2	-0.4	-1.6*	-2.2*
4	PR	0.8	4.0*	1.5	1.7	1.3	-2.4*	-1.5*
5	RV	0.8	4.5*	1.0	-0.3	-2.5*	-0.8	-0.2
6	R	0.0	2.1*	1.2	1.5	1.5	-0.4	-0.9
7	R	0.3	4.2*	1.5	1.0	1.4	-1.3	0.9
8	PRV	-0.7	2.2*	-0.2	-1.3	-2.5*	0.7	-1.8*

A cutoff z-score of 1.5 was used to mark areas of difficulty with an asterisk (*). Children were classified as having difficulties in the following areas: Rapid automatized naming (R): z-score ≥ 1.5 in total time required on the RAN task. Visual cognitive function (V): z-score ≤ -1.5 on either the 3-minute or 30-minute delayed reproduction task of the ROCFT. Phonological function (P): z-score ≤ -1.5 on either the reversed repetition task for 4-mora words or nonwords.

To assess the psychological burden related to reading and writing, as well as academic performance in Japanese language, we used selected items from the Inagaki Checklist for Reading and Writing Difficulties [3], which is commonly used in the differential diagnosis of developmental dyslexia. Specifically, we focused on the items related to psychological burden and academic ability (Japanese language). Although this questionnaire is typically completed through interviews with caregivers or other close adults, in this study we also asked the children themselves to report whether they experienced psychological burden related to reading (letters or texts) and writing (letters or texts). This allowed us to assess both external observations and children's self-awareness of their difficulties. As a result, all eight children, along with their caregivers, reported experiencing psychological burden in both reading and writing. Responses to the academic performance (Japanese language) section of the questionnaire were categorized into four levels: a delay of more than two grade levels (Case 1), a delay of one to two grade levels (Cases 3, 5, 7, and 8), a delay below the average for the current grade (Cases 4 and 6), and no delay (Case 2). This study was conducted with the approval of the Institutional Review Board of Akita International University (Approval No. 0217).

2. Haptic Reading Task Using Raised Text Plates

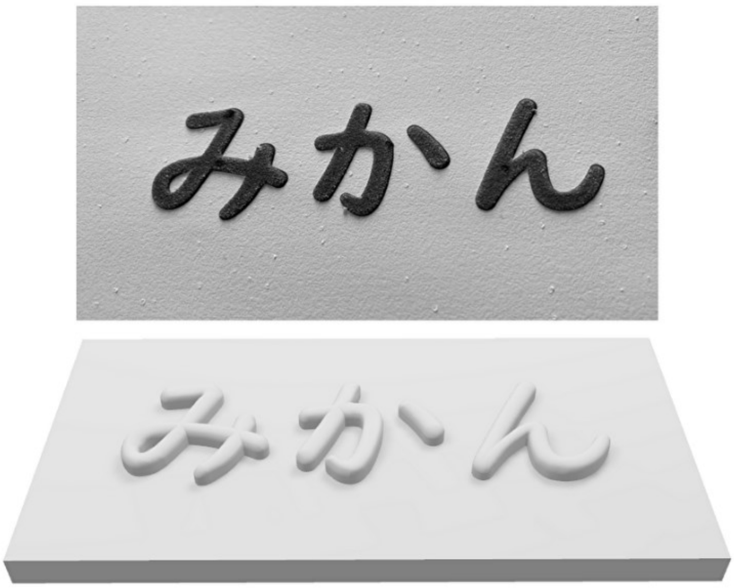

Figure 1. Method for Creating Letters on Haptic Reading Plates 3D data of the hiragana word "みかん" (mikan; bottom), and the printed letters (top) produced by a 3D printer with raised lines 0.5 mm in height and 3.0 mm in width, rounded in shape and painted black along the stroke lines.

Raised kana characters, kana words, and short sentences were designed using the 3D software Fusion 360 (Autodesk Inc.) and produced with a 3D printer by extruding character strokes into three-dimensional forms (see Figure 1). These raised characters were arranged on A4-sized haptic reading plates for use in multisensory learning tasks. A total of 14 haptic plates were created, divided into the following four types: ① Four plates with hiragana (71 characters) and katakana (71 characters), including basic, voiced, and semi-voiced sounds, each character raised at 62 pixels. ② Two plates for special syllables (e.g., "cha", "nya"), consisting of 27 hiragana and 27 katakana morae, each combining 62- and 32-pixel components. ③ Six plates containing kana words, each raised at 45 pixels per character, including 68 hiragana words and 68 katakana words, ranging from 2 to 7 morae. ④ Two plates of short kana sentences, each composed of 120 characters raised at 32 pixels per character. The design of the raised components was based on findings from a memory experiment using 3D versions of the Rey-Osterrieth Complex Figure Test (ROCFT) [12], in which tactile exploration while viewing figures with 0.5 mm height and rounded edges led to enhanced visual memory. Based on this evidence, the raised text plates used in this study were printed in UD Digital Textbook Font, with character strokes extruded to a height of 0.5 mm, width of 0.3 mm, and rounded top surfaces. The raised parts were painted black to ensure visual recognition of the characters, in addition to tactile perception.

3. Evaluation and Learning Procedure

1） Evaluation

As a pre-learning assessment (Time 1), participants completed the following subtests of the STRAW-R: the RAN task, rapid reading task, and kana dictation task (single characters) to evaluate their reading and writing skills. Following this, the participants completed 14 learning sessions over 40 days using the 14 haptic reading plates. Forty days after the initial assessment, the same STRAW-R subtests were administered again as a post-learning assessment (Time 2). Performance before and after the intervention (Time 1 vs. Time 2) was compared to examine the effects of the learning program. On the day of the post-assessment, participants were also asked to complete a self-report questionnaire, developed for this study, to evaluate changes in perceived psychological burden related to reading and writing. The questionnaire included two categories: (1) burden when reading letters or sentences, and (2) burden when writing letters or sentences. For each, children were asked to indicate whether the burden had decreased, increased, or remained unchanged during everyday life or school activities, and to provide a brief explanation of their response.

2) Learning Tasks and Haptic Reading Procedure

The learning program was implemented based on an established decoding instruction method [7], which combines in-person evaluation and guided monitoring. At the outset, each child and their caregiver received instruction on the reading/writing assessments and the procedures for haptic reading—specifically, how to touch the raised characters, the number of plates per session, and the target duration per activity. The distributed haptic reading plates were used repeatedly throughout the learning period, with occasional in-person monitoring sessions. The learning task involved reading aloud while visually and haptically exploring raised text across 14 plates. The plates were divided into four sections, practiced in sequential order (①→②→③→④), one section per day: ① Four plates of basic kana characters (hiragana and katakana), including unvoiced, voiced, and semi-voiced sounds. ② Two plates of special syllables (e.g., palatalized or nasal sounds such as "nya," "cha") in both hiragana and katakana. ③ Six plates of kana words (hiragana and katakana), ranging from 2 to 7 morae. ④ Two plates containing short kana sentences. One complete session—covering all 14 plates—was counted as a single round of learning, with a total of 14 sessions conducted. The duration of each session varied by individual; if a child was unable to complete all 14 plates in a single day, the task was divided across multiple days. Participants were given the following instructions for tactile interaction:

- For basic kana (hiragana and katakana), they were instructed to touch and read aloud each character slowly, using the pad of the middle finger to trace the raised shape while looking at it, aiming for at least two seconds per character.
- For special syllables (e.g., "nya," "ja," "pya"), they were instructed to trace the entire mora unit as a single chunk using the middle finger and read it aloud slowly.
- For kana words (2–7 morae), participants were guided to trace the entire word as a unit, not letter by letter, while visually tracking the text and reading it aloud at a slow pace.
- In short sentences, the same word-by-word haptic reading method was applied.

Approximately 20 days after the start of home-based haptic reading practice, an in-person monitoring session was conducted to help maintain the children's motivation. During this session, participants received feedback and guidance, including a review of how to properly touch the raised characters. The second assessment was conducted after the children completed the prescribed number of haptic reading sessions. To monitor learning progress at home, caregivers were given a checklist to record the date, duration, and number of plates completed for each session.

II. Results

The differences in z-scores between the first (pre-learning) and second (post-learning) administrations of the STRAW-R writing task, rapid reading task, and RAN task, as well as results from the subjective evaluation questionnaire, are presented in Table 3.

Table 3. Changes in STRAW-R Scores (z-score differences) and Subjective Evaluations After Haptic Reading Intervention

Dyslexia Cases			STRAW-R（Reading and Writing Achievement Levels）								Subjective Evaluation（Perceived Burden）	
			RAN	Reading Fluency					Auditory Writing			
No	Classification			Hiragana Word	Hiragana Non-word	Katakana Word	Katakana Non-word	Passage	Hiragana	Katakana	Reading	Writing
1	Reading	R	-6.1*	-3.7*	-1.5*	-4.1*	-0.7	-0.2	+1.6*	0.0	Improved	Improved
2	Reading & Writing	R	-2.0*	-1.6*	-0.1	-0.8	-0.6	0.0	+5.0*	0.0	Improved	Improved
3	Reading & Writing	PR	-2.3*	-5.0*	-1.7*	-3.6*	-1.5*	-1.1*	+3.3*	+0.7	Improved	No Change
4	Reading	PR	-2.0*	-0.4	-1.5*	-2.3*	-0.3	-0.2	0.0	+0.5	Improved	Improved
5	Reading	RV	+0.2	-0.9	0.0	0.0	-0.2	-1.1*	0.0	+0.5	No Change	No Change
6	Reading & Writing	R	-1.8*	-1.1*	-2.1*	-0.2	-1.2*	-1.3*	0.0	+5.0*	Improved	Improved
7	Reading & Writing	R	-1.3*	-1.4*	-2.0*	-3.0*	-2.3*	-4.1*	+1.6*	+1.9*	Improved	Improved
8	Reading	PRV	-2.4*	-1.6*	-1.5*	0.0	-0.1	-0.5	0.0	0.5	Improved	Improved

An asterisk (*) indicates scores with an improvement of z-score ≥ 1.0. RAN and rapid reading, a decrease in required time (−) was considered an improvement. For dictation, an increase in the number of correct responses (+) was considered an improvement. Subjective evaluation: After completing the 14 haptic reading sessions, children were asked separately about reading and writing whether they experienced a reduction in burden or no change.

1. Kana Dictation (Listening-to-Writing) Task (STRAW-R)

Among the four children who showed difficulties in writing single kana characters (Cases 2, 3, 6, and 7), all demonstrated an improvement of +1.5 or more in z-score for correct responses in at least one of the two dictation subtests. None of the four cases showed a decline greater than −1.0 z-score in any of the subtests. The most notable improvement was observed in Case 7, who showed z-score gains exceeding +1.5 in both of the tasks previously identified as areas of difficulty. Additionally, among these four children, the number of characters with a response delay of more than two seconds (from stimulus presentation to writing onset) decreased from eight to four characters. In the subjective evaluation questionnaire, three of the four children reported that "writing became easier", while Case 3 indicated "no change."

2. Rapid Reading Task (STRAW-R)

Among the eight children with reading difficulties, seven cases (Cases 1, 2, 3, 4, 6, 7, and 8) showed a reduction in reading time of +1.5 z-score or more in at least one of the five rapid reading subtests. All seven of these children also demonstrated a reduction in reading time of +1.0 z-score or more in at least two subtests. There was no significant difference between the number of improved items for real words and non-words. Importantly, none of the participants showed a deterioration in reading time greater than −1.0 z-score in any of the subtests. Case 7 exhibited the most notable improvement, with four subtests showing gains of +2.0 z-score or more, and one additional subtest with a gain of +1.0 or more. In contrast, Case 5 showed the least improvement, with only one subtest (sentences) demonstrating a gain of +1.0 or more. In the subjective evaluation questionnaire, all seven children who showed improvement across multiple items reported that their "reading burden had decreased." Case 5, who showed improvement in only one item, reported that there was "no change" in perceived reading burden.

3. RAN Task (STRAW-R)

Among the eight children who initially showed difficulties with the RAN task, seven cases (Cases 1, 2, 3, 4, 6, 7, and 8) demonstrated a reduction in the average completion time (in seconds) across the three RAN subtests. Of these, six cases (Cases 1, 2, 3, 4, 6, and 8) showed a z-score improvement of +1.5 or greater. Case 7 exhibited a reduction in time with a z-score improvement between +1.0 and +1.5. Only Case 5 did not show a meaningful reduction in RAN task performance time.

4. Analysis Based on Background Cognitive Function

We also analyzed each case individually from the perspective of cognitive processing involved in multisensory learning. In skilled learning tasks that require multisensory integration—such as typing practice involving visual, motor, and tactile input—the reminiscence effect has been observed, where memory consolidation over time leads to improved performance compared to immediately after training [18]. We hypothesized that individual differences in memory formation would influence the effects of haptic reading in this study. In a memory study using the Rey-Osterrieth Complex Figure Test (ROCFT) with elementary school students [16], it was reported that upper-grade students tended to perform better on delayed recall (30 minutes) than on immediate recall (3 minutes) after copying the figure, suggesting a reminiscence effect due to the consolidation of visual and motor information. In this study, children who showed a z-score decline of more than −1.0 between immediate and delayed recall were considered to have difficulty retaining information from multisensory input. This applied to Cases 5 and 8. Case 5 showed little improvement after training, and also reported no reduction in subjective burden. Case 8, on the other hand, demonstrated improvements in reading time for two rapid reading tasks (hiragana words and non-words) and in the RAN task. Conversely, children whose delayed recall scores improved over immediate recall (positive z-score change)—Cases 1, 2, and 7—were interpreted as having stronger retention of multisensory memory. Case 1 had initially struggled with all five rapid reading items, but showed reading time improvement in three of them. Case 2 had difficulties with one rapid reading item (hiragana words) and two dictation items, including a severe deficit in recalling hiragana ($z = -8.0$). After the intervention, the child showed improved performance in one rapid reading item and a substantial gain ($z = +5.0$) in the hiragana dictation task. Hiragana that could not be written without delay at baseline was later written without hesitation. Case 7 showed the greatest number of improvements across all participants, with gains in four out of five rapid reading tasks and one dictation item. Additionally, both the child and caregiver reported positive behavioral changes, such as "started reading manga" and "no longer avoids writing homework," indicating not only improvement on the STRAW-R assessments but also observable changes in daily literacy behaviors.

5. Observed Changes During Haptic Reading Practice

In this study, in-person instruction and monitoring were conducted approximately 20 days after the start of the haptic reading program. A notable observation was that Cases 1, 2, and 6 became able to perform haptic reading of individual kana characters with their eyes closed. Although the haptic reading tasks in this study were designed to be performed with visual guidance, unlike Braille for individuals with visual impairments, these three children, who were initially unable to identify kana through touch alone, gradually became able to recognize kana characters without visual input during the course of practice. It should be noted that this change was observed spontaneously, as the children showed interest and voluntarily attempted haptic reading with their eyes closed. No such behavior was observed in the other participants. Furthermore, Cases 1, 3, 4, 6, and 7 showed a transition in kana word reading from sequential haptic reading—touching and reading one character at a time—to a more fluent haptic reading style in which entire words were read as a single tactile unit. In Cases 2 and 8, their initial method of tracing the strokes of kana characters with their fingertips changed into a more exploratory haptic reading approach, using the pads of their fingers to perceive the overall character shape. In contrast, Case 5 exhibited no noticeable change in haptic reading behavior throughout the intervention.

III. Discussion

The observed improvements in writing accuracy and reductions in reading time are discussed here in relation to active haptic perception. In a prior memory experiment using raised ROCFT figures with the same height and shape as the haptic reading plates used in this study [12], it was found that combining visual observation with tactile exploration significantly improved recall performance. The study suggested that active haptic perception enhanced attention to the structural features of complex figures, thereby facilitating memory formation and retrieval. Similarly, in the present study, the four children who showed improvement in kana dictation accuracy (Cases 2, 3, 6, and 7) likely benefited from being able to touch and explore the large, raised kana characters (65 pixels per character) while reading aloud. This multimodal experience may have promoted more concrete and stable formation of character-shape memory. In the kana dictation (listening-to-writing) task, the total number of delayed responses exceeding two seconds between auditory presentation and writing onset decreased from eight characters before the intervention to four characters afterward across the four children who had writing difficulties. This improvement in character recall may be associated with the subjective reports from three out of four children, who indicated that "writing became easier" following the intervention. Furthermore, the formation of concrete and refined mental representations of character shapes through haptic perception may also have contributed to the observed phenomenon in three children, who became able to recognize individual kana characters by touch even with their eyes closed. In the rapid reading task, seven out of eight children (Cases 1, 2, 3, 4, 6, 7, and 8) demonstrated reduced reading times.

This suggests that character-shape memory formed through haptic learning may have facilitated top-down visual processing, thereby enhancing character recognition. A prior international study [11] also reported that tactile exploration of raised alphabet letters led to improved performance in decoding tasks. The authors of that study proposed that haptic perception, which integrates simultaneous visual information and sequential phonological information, helped learners become more consciously aware of the connection between spelling and pronunciation, thus strengthening memory traces. Likewise, in the present study, reading aloud while receiving haptic feedback from raised kana characters may have supported the efficient formation of letter–sound associative memory. Although the haptic learning materials (raised kana plates) were designed to exclude any words overlapping with the rapid reading tasks in the STRAW-R, improvements in reading speed were observed not only for meaningful words but also for nonwords. This suggests that the observed changes were not simply due to improved word-form recognition, but rather resulted from enhanced recognition of individual kana character shapes and the formation of letter–sound associative memory. Such memory formation likely contributed to: greater decoding efficiency in the rapid reading tasks, by facilitating the process from visual character recognition to phonological decoding, and improved encoding efficiency in the dictation tasks, by supporting the recall of character shapes from phonological input. During the monitoring conducted during the intervention period, a shift was observed in some participants from reading each kana character individually to reading entire words as a chunk using unified tactile tracing. This shift suggests that the tactile feedback during reading may have increased the level of arousal, thereby facilitating chunking of memory from character-level to word-level units. Among the 8 children who showed improvements in reading speed in the rapid reading tasks, 7 reported in the subjective evaluation questionnaire that reading had become easier, indicating a perceived reduction in cognitive burden. In contrast, Participant 5, who showed improvement in only one item (sentence reading), reported "no noticeable change," which was consistent with their limited objective improvement in the STRAW-R results. These findings suggest that improved character recognition, enhanced efficiency in converting letters to sounds, and the facilitation of word-form recognition may have contributed to a reduced subjective burden of reading in the participants. In this study, we focused on the difference in performance between the 3-minute and 30-minute delayed recall tasks in the ROCFT (Rey-Osterrieth Complex Figure Test) to analyze each child’s memory retention characteristics. Among the children whose scores improved over time ("positive change group"), Case 7, who showed the greatest number of improvements across tasks, was included. In contrast, among those whose scores declined ("negative change group"), Case 5, who showed the fewest improvements, was included. Particularly in Case 5, the child lacked a top-down strategy of constructing the figure from the whole to the parts during the initial copy phase. Although the overall shape was reproduced at the 3-minute recall, by the 30-minute recall the child could no longer recall the whole figure and instead reproduced only fragmented features, indicating a significant decline in visual memory retention. While the ROCFT copy task and haptic reading involve different sensory modalities, it is possible that a weakness in central integration—specifically, the ability to synthesize parts into a coherent whole—also affected the child's ability to encode and retrieve tactile memory of letter forms. Thus, the results suggest that haptic-enhanced learning does not necessarily facilitate memory encoding for all learners, and that some children—such as Case 5—may have cognitive profiles that are not well-suited to haptic learning methods. On the other hand, although Case 8 showed a decline in memory performance between the immediate and delayed ROCFT recall, improvements were still observed in two rapid reading tasks and the RAN task. This implies that ROCFT-based memory retention alone may not sufficiently capture the cognitive characteristics that predict responsiveness to haptic learning. Future studies should consider using tactile memory tasks more closely aligned with haptic reading activities to better evaluate their effectiveness. In the RAN (Rapid Automatized Naming) task, 7 out of 8 participants (Cases 1, 2, 3, 4, 6, 7, and 8) showed reduced naming times after the intervention. In contrast, Case 5, who exhibited minimal changes in both reading and writing tasks, also showed no significant improvement in the RAN task. The RAN task, which involves alternating between reading digits and pictures aloud, requires the rapid retrieval of phonological information from visual stimuli and efficient shifts in attention. These processes involve complex cognitive functions related to the development of reading automatization. The haptic reading tasks used in this study did not include numerical or pictorial stimuli like those used in the STRAW-R's RAN subtest. Therefore, the observed improvement in RAN performance cannot be directly attributed to the content of the learning material. It is more likely that the improvements reflect indirect enhancements in cognitive processing efficiency resulting from the multisensory training. However, since the re-assessment was conducted only 40 days after the initial evaluation, this time interval falls short of the typical one-year interval generally recommended for standardized cognitive testing. As such, retention of the original digit or picture sequence may have influenced the RAN performance at follow-up, and this potential confound should be taken into account when interpreting the results. However, considering the magnitude of performance changes observed after a single session, it is unlikely that the improvements in the RAN task resulted from mere test–retest or priming effects. Given that the RAN task demands multiple cognitive processes—such as the retrieval of phonological information from visually presented stimuli and rapid attentional shifting—priming effects are considered minimal in such tasks. In the domain of language processing, two well-known retrieval routes are described: the naming route, which retrieves spoken words via the phonological lexicon from semantic memory, and the writing route, which retrieves orthographic word forms via the visual lexicon. Previous reports on aphasia have demonstrated that the visual presentation of a word-initial letter can facilitate naming performance by activating the phonological lexicon through the visual lexicon pathway [19]. Based on these findings, the improvement in RAN performance in this study may be attributed to enhanced retrieval of phonological information from the visual lexicon, supported by strengthened letter-form memory acquired through haptic reading training. In the haptic reading approach used in this study—where participants "look, touch, and read aloud" using embossed letters—multisensory integration of visual, tactile, and auditory inputs is required. It is plausible that haptic feedback functioned as a bridging modality that linked semantic memory with both the visual and phonological lexicons. The retrieval of visual word forms (orthographic representations) may have facilitated the activation of their corresponding phonological representations (spoken words). In light of future investigations using neuroimaging, a study examining the developmental changes in naming ability and brain structure [20] has shown that, with the development of naming skills, connectivity increases between the left fusiform gyrus and other brain regions—such as the left parahippocampal gyrus and the opercular part of the left inferior frontal gyrus—which are involved in memory encoding and phonological lexicon processing. The left fusiform gyrus is known to play a key role in the integration of visual and tactile information and functions as part of the visual word form area (VWFA), which is involved in recalling letter shapes and recognizing word forms during reading and writing. Therefore, the multisensory reading activity implemented in this study—which engaged visual, tactile, and auditory modalities—may have influenced changes in the connectivity of neural networks centered around the left fusiform gyrus. Although the precise mechanism by which naming speed improves through haptic reading remains unclear, further verification through brain imaging techniques such as fMRI will be necessary. This study was a case series involving only eight children. As a next step, we aim to investigate the effects and mechanisms of haptic reading more precisely by not only measuring changes in brain function following the intervention, but also by conducting a controlled comparison study between an intervention group and a non-intervention group.

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