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Evaluating correlations between reading ability and psychophysical measurements of dynamic visual information processing in Japanese adults

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The reading ability of English readers has been shown to correlate with psychophysical measurements of dynamic visual information processing. This study investigated the relationship between reading ability and dynamic visual information processing in healthy adult native Japanese readers (n = 46). Reading ability was assessed using three different tests: the Japanese Adult Reading Test (JART), transposed-letter detection task, and oral reading. Principal component analysis was performed on the scores on the three reading tests to quantify reading ability. Psychophysical thresholds were measured for contrast detection and speed discrimination with a drifting grating stimulus as well as for tracking two targets among concentrically revolving objects, providing an upper speed limit for attentional tracking. Simple correlation analysis revealed that one of the principal components correlated with the tracking speed limit. In addition, another principal component correlated with the speed-discrimination threshold, which is consistent with previous findings in English readers. These results suggest that Japanese reading ability involves at least two different processes, each sharing underlying mechanisms with visual motion and attentional processing.

Keywords Japanese reading ability, Dynamic visual information processing, Contrast detection, Speed discrimination, Multiple object tracking, Individual differences

Reading is a highly important cognitive function that is essential in education, work, and other social life situations requiring a wide range of textual communication. Reading requires the recognition of a visual word form (i.e., orthography) based on visual analysis of retinal input in the posterior cortex and subsequent specialized analysis via the visual word form area, located in the ventral occipitotemporal cortex[1]. Visual word form information is then translated into sound (i.e., phonological) and meaning (i.e., semantic and lexical) information, which involves auditory and language areas, and possibly the intraparietal sulcus (IPS), neurophysiologically[2,3].

There are abnormalities (dyslexia)[4] specific to reading ability, which vary considerably even among healthy individuals. The limiting factors of reading ability, which have been the subject of psychological and neurobiological research, range from low-level factors in sensory and motor systems[5] to high-level language processing and cognitive factors including working memory, word learning, and reading experience[6].

A deficit in accessing and manipulating phonological information is considered a major factor that limits reading performance[7–10]. This view is supported by the fact that the most common cognitive disorder in reading ability involves difficulties in decoding sounds[11], such as rhyming skills[12]. However, some individuals with dyslexia did not show phonological deficits (e.g.,[13]), and others reported difficulties in seeing texts rather than

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decoding sounds (e.g.,[14]). It has also been argued that learning to read may improve phonological skills rather than vice versa[15,16].

Alternatively, it has been hypothesized that impairment of the magnocellular layer of the lateral geniculate nucleus (LGN) and subsequent processing limits reading performance[14,17,18]. Visual information from the retina is first transmitted to the LGN, which consists of three functionally distinct subdivisions (the magnocellular, parvocellular, and koniocellular). Among these subdivisions, magnocellular subdivisions exhibit high contrast sensitivity and greater temporal resolution, but lower spatial resolution, whereas parvocellular subdivisions exhibit greater spatial resolution and chromatic selectivity, but lower temporal resolution[19–22]. For this reason, visual neuroscientists hypothesized that a series of visual processes from the magnocellular subdivision to the motion-selective cortical area MT and from the parvocellular subdivision to the color-selective cortical area V4 are responsible for different visual functions, such as motion and color perception, respectively[23,24]. The idea that the properties of magnocellular deficits are related to reading performance is derived from anatomical observations that postmortem brains of patients with dyslexia showed a smaller magnocellular volume[17] and psychophysical observations[18], although the simplistic model emphasizing the importance of the magnocellular system is controversial in the field[25,26].

Consistent with the magnocellular hypothesis[27], the relationship between English reading ability and visual motion processing has been demonstrated by assessing individual differences: individuals with dyslexia or those with lower scores in reading tests often show poorer performance in coherent motion detection[28–33] (but see[34]) and speed discrimination[35,36], while such a correlation does not hold for contrast detection[35,36]. In addition, since such a correlation with speed discrimination was not identified when reading ability was assessed using pseudowords, a previous study suggested that motion processing is correlated with the word familiarity aspect of reading rather than letter-by-letter analysis[36].

Other studies have proposed a role of attention in reading by demonstrating that individuals with dyslexia perform worse than typically developed controls in visual flanker and search tasks[37,38]. This role may stem from the hypothesized relationship between reading ability and magnocellular (or extensively dorsal) visual function[16,31,39] as well as the known relationship between attention and the temporal sensitivity of visual processing[40,41]. However, one study reported that individuals with dyslexia performed worse than typically developed controls in visual search but equally well in global motion detection[42] (but see[28]). These mixed findings indicate the necessity of performing studies to acquire visual motion and attentive tasks in the same individuals to assess their correlations with reading ability, to better understand how individual differences in performance are related across psychophysical tasks, and to better understand the underlying relationship between reading and visual processing.

While these previous studies demonstrated that individual differences in reading ability likely reflect multiple factors, including phonological, magnocellular, and attentional processing, it is important to note that most of these studies focused on English readers; therefore, the evidence on the generalization of findings into different language systems remains challenging.

English reading has very different properties from those in other languages. In this study, we used Japanese because it differs significantly from English in several respects. Notably, Japanese is a head-final language, whereas English is a head-initial language, leading to substantial differences in word order. Regarding orthography, English relies solely on an alphabetic script, whereas Japanese employs three distinct scripts: *kanji* (Chinese characters) and the syllabic scripts *hiragana* and *katakana*. *Katakana* is commonly used for foreign names, places, and loanwords, while *hiragana* is often utilized for words that do not have corresponding *kanji* characters. Both *hiragana* and *katakana* consist of 46 basic characters, which can represent around 110 sounds when combined with diacritical marks (e.g.,[43]). Consequently, the *kana* (*hiragana* and *katakana*) scripts exhibit a "transparent" orthographic system, where there is a one-to-one correspondence between orthography and phonology, similar to the writing systems of languages like Italian or Spanish. Contrastingly, *kanji* and English have "opaque" scripts, as their writing systems do not always maintain a one-to-one correspondence between orthography and phonology.

In fact, a case was reported in which a 16-year-old English/Japanese bilingual person had difficulty reading only in English while reading in Japanese was normal; other cognitive functions were comparable between English and Japanese[43]. Therefore, it is important to assess the extent to which the observed correlation between reading ability and psychophysical performance can be seen in readers in a different language system, such as Japanese, to understand whether such correlational effects are universal among language systems.

To investigate the relationship between Japanese reading ability and dynamic visual information processing, reading scores derived from a set of reading tests (see Methods) and psychophysical thresholds of basic visual function were compared across participants. For psychophysical measurements, contrast-detection and speed-discrimination thresholds were determined to assess the involvement of visual motion processing, while separating the involvement of motion sensitivity (speed discrimination from contrast detection), as described by Main et al.[36]. In addition, the upper speed limit of revolving objects to be covertly tracked was determined to assess the involvement of attentional processing (e.g.,[44]). The employment of an object-tracking task was also motivated by functional neuroimaging studies suggesting a role for the IPS in reading[2,3] and attentional tracking[45–47].

Methods

Participants

Forty-six native Japanese readers participated (31 women; 18–48 years old, $M = 33.4$, $SD = 9.4$). All participants were right-handed and had no history of reading disorders (e.g., dyslexia). They were not informed of the purpose of the study. The participants were recruited via convenience sampling and compensated for their participation. The sample size was determined before data collection. Given that our study was fundamentally a cross-linguistic replication, we based our power analysis on effect sizes reported in previous research. We defined the effect size as pragmatically meaningful and designed the sample size accordingly. Based on a previous study showing a correlation between English reading rate and speed-discrimination threshold[36], we expected a moderate effect in the order of ~ 0.4, indicating that 44 participants should be sufficient to achieve high statistical power (0.8) for a correlation analysis, according to calculations using G*Power 3 software[48]. The present study was not preregistered. All the participants provided written informed consent. Before experiments were conducted, all the participants were asked to participate in a battery of tests for visual performance, such as visual acuity, astigmatism, and stereopsis. Through this screening procedure, we confirmed that all the participants had normal or corrected-to-normal vision. This study was conducted in accordance with the Declaration of Helsinki (2003) and approved by the Ethics Committee for Human Research of the National Institutes of Natural Sciences.

Reading tests

To the best of our knowledge, there is no established Japanese test battery proven to be directly comparable to those used to test English reading abilities (e.g., TOWRE-2[49]). For this reason, we used a set of three different reading tests, the Japanese Adult Reading Test (JART), transposed-letter detection task, and oral reading, for identifying principal components shared among multiple reading tests, as a marker for evaluating Japanese reading ability. Each participant was tested in the order of JART, transposed-letter detection, and oral reading, prior to the psychophysical experiments. Notably, the standardization of Japanese reading tests is less rigorous than English tests, and the three tests we used do not necessarily measure independent abilities. Instead, the abilities reflected in their scores are likely to overlap to some extent.

Japanese Adult Reading Test (JART)

The JART was developed by Matsuoka et al.[50] and is based on the National Adult Reading Test (NART[51–53]). The NART is an English reading test consisting of 50 irregularly spelled words (e.g., naïve) designed to measure the premorbid IQ of dementia patients. These irregularly spelled words were chosen to assess familiarity with the words, without assessing the ability to decode unfamiliar words phonetically[51]. The JART measures the reading scores of 50 Japanese *kanji* compound words whose orthography–phonology relationship is word-specific[50]. We used the JART to measure participants' reading ability based on word familiarity. The JART score was converted to a Verbal Intelligence Quotient (VIQ[50]) using the following estimation formula:

$$\mathrm{VIQ} = 127.8 - 1.093 \times \text{number of errors} \tag{1}$$

We asked the participants to write the pronunciations of the 50 *kanji* words using *hiragana* or *katakana* in this study. This protocol deviates from Matsuoka et al.[50], who asked participants to report pronunciation orally. Given that the present study aims to examine the reading performance of healthy adults, there are no concerns about handwriting difficulty, unlike patients with dementia tested in Matsuoka et al.[50]. Therefore, we opted for a written response to ensure the accuracy and consistency of measurements. Additionally, writing the pronunciation of *kanji* words in *kana* is a common activity among Japanese readers. While *kanji* does not always correspond one-to-one with pronunciation, *hiragana* and *katakana* correspond one-to-one with pronunciation. Japanese people are trained to learn the pronunciation of *kanji* words by reading texts with *kanji* words and small *kana* letters above or beside *kanji,* indicating their pronunciation from elementary school. This makes it common to transcribe *kanji* pronunciations into *hiragana* and *katakana* scripts.

The time required to complete the JART was approximately 5–10 min. Further details of the JART are described in Matsuoka et al.[50].

Transposed-letter detection task

Pseudowords with transposed letters are easily confused with their base words (e.g., participants tend to read chocolate instead of the pseudoword cholocate[54]). This phenomenon has been used to elucidate the letter encoding process in visual word recognition (e.g.,[55–59]). From a slightly different perspective, this phenomenon may reflect whether individuals engage in top-down or bottom-up language processing. If participants read sentences bottom-up and analyze them letter by letter, they quickly notice that letters are transposed in relation to the lexicon. However, if participants read sentences top-down, they would not notice the transposed letters. Therefore, based on the transposed-letter effect in English reading (e.g.,[60]), we measured the detection performance of transposed letters embedded in Japanese texts and examined the characteristics of participants' language processing.

For creating such transposed-letter stimuli, six texts (poems, stories, explanations, etc.) of approximately 100 to 150 characters were selected from Japanese textbooks for first and second grade junior high school students[61–64]. Five transposed-letter patterns were created for each text type. Each pattern contained 1–4 transposed letters. The transposed letters did not overlap with the other patterns. There were 30 transposed-letter detection questions (see Supplementary Fig. 1). Questions were distributed in booklets printed on paper. The font of the printed characters was "Yu Gothic Regular" and had a size of 20 points. One question was printed on each page. The presentation order of the 30 questions was randomized such that the same text was not repeated in a row. Four presentation order patterns were prepared.

The original text without transposed letters was read by the participants for a few minutes before the transposed-letter detection task. The participants were then asked to circle the letter sequence if they found the transposed letters for each question. Participants were also instructed to respond within 30 s per question. This task took approximately 25 min including instructions.

Oral reading task

We used an oral reading task to assess each participant's reading ability. Oral reading likely reflects abilities across several specific processing stages, including sensory, lexical, and phonological processes. Oral reading is widely used as part of major reading test batteries in English, such as the TOWRE[49] and the Woodcock–Johnson IV Basic Reading Score[65]. In this study, we employed a simple oral reading test based on the token test developed by Koeda et al.[66] to diagnose dyslexia in the Japanese population. In this task, three white cards (297 mm wide and 210 mm high) containing a short sentence of 23–27 morae (see Supplementary Fig. 2 for an example) were presented to participants sequentially. Participants were asked to read the sentences orally as quickly and accurately as possible. Each card contained a sentence with a mixture of words written in *hiragana* and *kanji*. As for each participant's reading performance, we measured the time it took to complete oral reading for all three sentences.

Psychophysical experiments

For each participant, psychophysical thresholds were measured after the completion of practice trials in the following order: contrast detection, speed discrimination, and object tracking. Each of the three psychophysical tasks took approximately 25–30 min. The images were displayed on a gamma-corrected 32-inch LCD screen (1920 × 1080 resolution; 1280 × 720 resolution for the object-tracking experiment) at a frame rate of 120 Hz (Display++, Cambridge Research Systems Ltd.). The images were generated on a computer (Ubuntu Linux 20.01 with a Radeon Pro WX3100 graphic board) under the control of MATLAB (Mathworks Inc.), Psychophysics Toolbox[67,68], and Vision Toolbox[69]. The screen resolution was 2.9 min/pix (3.7 min/pix for the object-tracking experiment) at a viewing distance of 66 cm constrained by a chin rest for binocular viewing. A neutral density filter placed in front of the participants' eyes (affixed to a chin rest) reduced the mean screen luminance to 3.6 cd/m^2 [36]. The visual stimuli were designed following the stimulus designs used in Main et al.[36] for the contrast-detection and speed-discrimination experiments and those used by Holcombe and Chen[70] for the object-tracking experiment.

Contrast detection

Each trial consisted of two temporal intervals of 0.4 s with an inter-stimulus interval of 0.25 s and a response period (Fig. 1A). In each trial, participants were asked to maintain their gaze on a black fixation dot (0.25 deg in diameter) presented at the center of the screen on a uniform gray background. In either the first or the second interval, a vertical sinusoidal grating (spatial frequency = 0.49 cycles/deg) that is contrast-modulated according to an isotropic Gaussian function (SD = 2.04 deg) appeared at the center for 0.4 s. For the stimulus onset and offset, the grating contrast was gradually ramped up and down by a 0.1-s long raised-cosine function. The grating drifted horizontally at 30.53 deg/s, and the leftward or rightward motion direction was switched in each trial. A beep was heard at the first and second intervals to inform participants. The response period lasted until participants indicated the temporal interval with the grating by pressing a key (two-interval forced choice, 2IFC).

In the first 72 trials, the grating contrast was adjusted by a staircase with a factor of two (e.g., 12.5%, 6.25%, 3.13%, 1.56%, 0.78%, and 0.39%) and a 1-up-2-down rule, which targeted a correct rate of 0.71. Five additional trials with a grating contrast of 99% were randomly intermixed into the staircase trials as catch trials. In the final 144 trials, the grating contrast was manipulated according to the method of constant stimuli; six levels, with 24 trials per level, were randomly interleaved. Six levels were determined for each participant as grating contrasts that yielded correct response rates of 0.55, 0.65, 0.75, 0.85, and 0.95, by fitting a logistic curve to the staircase data using the maximum likelihood method, in addition to the grating contrast of 12.5% common to all participants.

Speed discrimination

The composition of each trial was the same as those intervals of the contrast-detection task, except that the grating stimulus appeared in both the first and second intervals (Fig. 1B), one drifting at 30.53 deg/s (standard stimulus), and the other at a speed that varied across trials (comparison stimulus). Grating contrast was randomized across trials to 16% or 24%. During the response period, participants indicated the temporal interval with the faster grating by pressing a key (2IFC).

In the first 72 trials, the grating speed of the comparison stimulus was adjusted using a staircase with a factor of 1.07 (e.g., 26.58, 28.49, 30.53, 32.72, and 35.07 deg/s) and a 1-up-1-down rule, which targeted a correct rate of 0.5. Five additional trials with comparison speeds of either 15.27 deg/s or 61.06 deg/s were randomly intermixed with the staircase trials as catch trials. In the final 144 trials, the comparison speed was manipulated according to the method of constant stimuli, and six levels, with 24 trials per level, were randomly interleaved. The six levels were determined for each participant as the comparison speeds that yielded response rates of 0.05, 0.23, 0.41, 0.59, 0.77, and 0.95 for reporting the comparison stimulus as the faster grating, by fitting a logistic curve to the staircase data with the maximum likelihood method.

Object tracking

Each trial consisted of an instruction period for two targets among the revolving objects (1 s), a tracking period (2–3 s), and a response period (Fig. 1C). The stimulus comprised three concentric rings of three objects equally spaced about the circular trajectory centered on a white fixation dot (0.29 deg in diameter) presented at the center of the screen on a uniform black background. Each object was a full-contrast Gaussian patch scaled by the eccentricity of the three rings (SD = 0.14 deg for inner, 0.24 deg for middle, and 0.43 deg for outer; eccentricity = 0.76 deg for inner, 2.29 deg for middle, and 6.11 deg for outer). These values were chosen to keep the rings well outside each other's crowding zones[71,72], as in Holcombe and Chen[70].

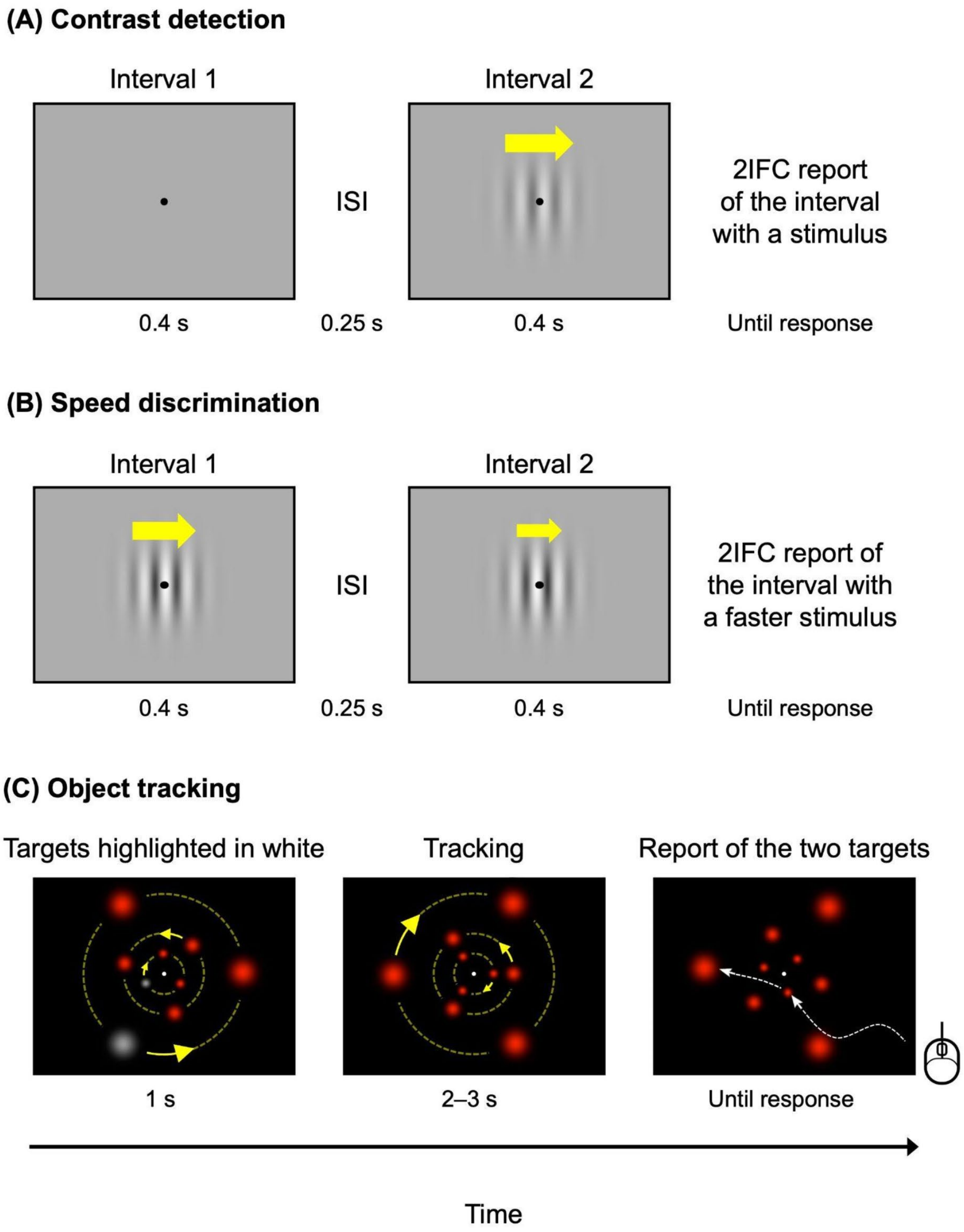

Fig. 1. Psychophysical experiments. (**A**) Contrast detection. A drifting grating stimulus was presented on the center of the screen during either the first or the second interval. Participants reported which interval contained the grating (2IFC). A small black dot on the center of the screen served as a fixation point. ISI: inter-stimulus interval. (**B**) Speed discrimination. A drifting grating stimulus was presented on the center of the screen during the first and the second intervals at either the same or different speeds. Participants reported which interval contained the faster grating (2IFC). Yellow arrows illustrate the grating motion within its envelope. (**C**) Object tracking. Participants tracked two targets among revolving objects and identified the targets after the objects stopped. They were asked to maintain fixation on the fixation point (white dot at the center of the screen). Yellow arrows and dashed curves illustrate the revolution of the objects on each ring and their circular trajectories. White arrows with dashed curves illustrate a cursor trajectory for clicking on the two targets with a computer mouse.

In each trial, participants were asked to maintain their gaze on the fixation dot. All objects in each ring revolved in the same direction and speed, starting from a random initial phase. During the instruction period, two objects randomly selected from two different rings were highlighted in white (targets; 7.1 cd/m^2) while the other objects remained red (distracters; 0.8 cd/m^2; evoked by red gun only). The targets gradually changed to red (identical to the distracters) over 1 s via a linear ramp in the RGB space. During the subsequent tracking period, each ring underwent a reversal in the motion direction at random intervals longer than 1 s. The objects were stopped after a random duration of 2–3 s. During the response period, the objects remained in the final positions until the participants indicated which two of the objects were the targets by clicking them with a computer mouse. The objects were replaced with those used in the next trial.

In 144 trials, the revolution speed was adjusted by a staircase with a step size of 0.2 revolution/s (e.g., 0.8, 1.0, 1.2, 1.4, and 1.6 rps) and a 1-up-1-down rule, targeting a correct rate of 0.49 (for correctly reporting both targets). An additional five trials with a revolution speed of 0.2 rps were randomly intermixed as catch trials.

Data analysis

Threshold determination

The contrast-detection threshold was determined as the grating contrast that yielded a correct response rate of 0.75, by fitting a logistic curve to the data obtained from the method of constant stimuli with the maximum likelihood method. For three participants, the fit did not converge, and was instead performed on the staircase data. The speed-discrimination threshold was determined as the grating speed of the comparison stimulus, which yielded a response rate of 0.75 for reporting the comparison stimulus as a faster grating by fitting a logistic curve to the data obtained from the method of constant stimuli with the maximum likelihood method. For four participants, the fit did not converge and was performed on the staircase data; however, for two of them, the fit still did not converge, and their speed-discrimination thresholds could not be determined. Therefore, data from the remaining 44 participants were used for subsequent analyses. The threshold speed was converted to the Weber fraction by subtracting the grating speed of the standard stimulus and dividing it by the grating speed of the standard stimulus. The object-tracking threshold was determined as the revolution speed that yielded a correct response rate of 0.49, by fitting a logistic curve to the data with the maximum likelihood method.

Evaluation of correlations between reading and psychophysical performance

We aimed to calculate the Pearson correlation coefficients between the reading test scores and psychophysical thresholds for comparison with those previously reported for English readers[30,32,33,35,36]. While we conducted three reading tests, it is unclear how much each test uniquely explains different aspects of reading performance. This is because Japanese reading tests are not as standardized as English. Thus, it is challenging to consider three reading tests as independent measurements, as there is no established relationship among them. Given that reading scores in different reading tests are likely correlated with each other, it is common for researchers to perform redundancy reduction, such as principal component analysis (PCA), on scores in multiple reading tests to estimate general reading performance[73]. For this reason, we performed PCA on the scores of the three reading tests (JART, transposed-letter detection, and oral reading) and calculated the Pearson correlation coefficients between the principal component (PC) scores and psychophysical thresholds. Using the pca function in the MATLAB Statistics and Machine Learning Toolbox, we identified PCs derived from the z-transformed scores of the three reading tests. Given the low dimensionality of our dataset on three reading tests, we only identified three PCs. As all three PCs explain a considerable variance, we retained all components without applying an eigenvalue cut-off and transformations (e.g., varimax rotation) to preserve information relevant to the reading ability.

Statistics and reproducibility

We evaluated the reliability of each reading test by calculating internal consistency. To this end, we calculated Cronbach's α as a reliability measure of reading tests using JASP statistical software[74] by the following estimation formula:

$$Crobach's\,\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k}\sigma_i^2}{\sigma^2}\right) \tag{2}$$

where k is the number of variables (i.e., 50 words for JART, 84 transposed letters, or 3 oral reading texts), σ is the variance in the total score of all the variables, σ_i is the variance in the score of each variable across participants.

As we aimed to interpret each PC and examine whether it correlated with the threshold for any psychophysical measurements, we tested a null hypothesis of Pearson correlation and corrected for multiple (3) comparisons, allowing for a false discovery rate (FDR) of 0.1. The significance level (α) was set at 0.033, equivalent to $P = 0.05$ with the FDR correction[75].

Results

Reading tests

We first assessed the reliability of our reading tests. For JART, Cronbach's α was 0.93 across participants (95% $CI = 0.90$–0.95). For oral reading, Cronbach's α was 0.90 (95% $CI = 0.84$–0.94) between three texts, with only four reading errors among all participants. For transposed-letter detection, Cronbach's α was 0.95 (95% $CI = 0.94$–0.96). These results indicated sufficient reliability of reading test measurements for further analyses.

Next, we evaluated the degree of individual differences in the reading test scores (Fig. 2A). The JART-estimated VIQ was greater than 90 for all participants ($M = 110.5$, $SD = 8.1$), consistent with no history of reading disorders. Oral reading time ranged from 10.9 to 19.9 s ($M = 14.5$ s, $SD = 1.9$ s), and transposed-letter detection accuracy ranged from 28.6% to 97.6% ($M = 70.3\%$, $SD = 19.2\%$). All data fell within ± 2.8 SD of the mean for each test; because of the low variance of the measurements, no data were excluded as outliers. Given the somewhat non-normal distributions, nonparametric Spearman correlation coefficients were also reported for significant results to ensure robustness.

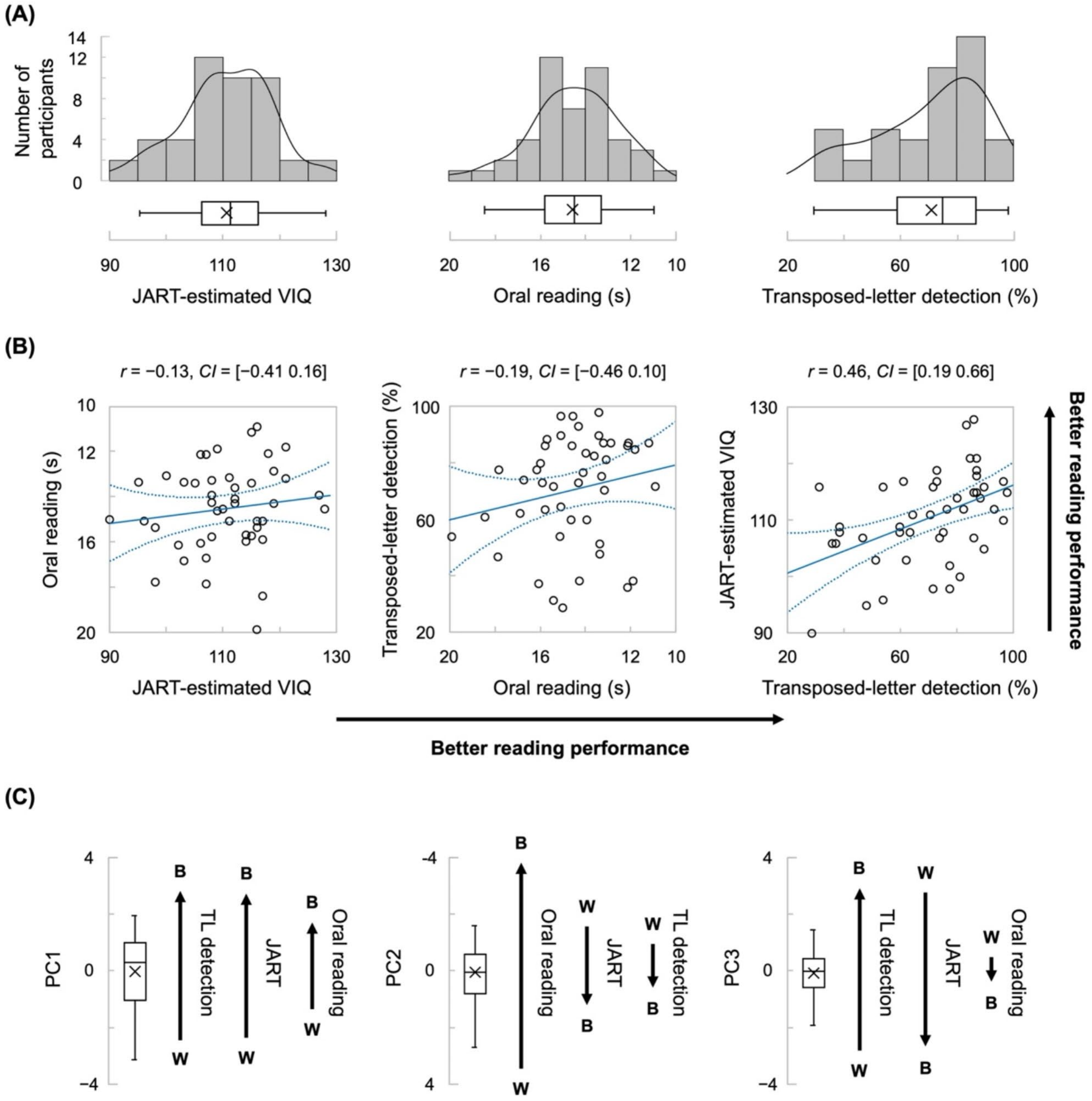

Fig. 2. Reading test results. (**A**) Distribution of individual scores in all three reading tests. Boxplots display the interquartile range, median, maximum, minimum, and mean (cross) for each test. The distributions show histograms and estimated probability density distributions, created using JASP with "Sturges" bin width type. (**B**) Scatterplot of individual scores compared across tests. Blue lines indicate linear regression, and dotted curves show the 95% *CI*, respectively. Arrows indicate the direction of better performance. (**C**) Boxplots display the interquartile range, median, maximum, minimum, and mean (cross) for three principal components (PCs) of reading performance identified by principal component analysis. Arrows indicate the relative sizes and performance directions of the PC coefficients. TL detection: transposed-letter detection. B: better performance. W: worse performance.

We then compared the individual reading scores across different tests (Fig. 2B). A significant correlation was found between JART-estimated VIQ and transposed-letter detection (right plot; $r=0.46$, $p=0.001$; $r_{\text{Spearman}}=0.45$). Oral reading did not show a statistically significant correlation with either JART-estimated VIQ (left plot; $r=-0.13$, $p=0.38$) or transposed-letter detection (middle plot; $r=-0.19$, $p=0.20$).

In line with our correlation analyses of the reading scores, suggesting at least one shared component across the different reading tests, we derived three principal component (PC) scores from the reading test data to reduce redundancy[73] (see Methods; boxplots of Fig. 2C). The relative contributions (eigenvalues) were 0.52 for PC1, 0.30 for PC2, and 0.18 for PC3. As all PCs explain a considerable variance, we retained all PCs in subsequent analyses to avoid losing information relevant to reading ability. The PC coefficients for JART-estimated VIQ, oral reading time, and transposed-letter detection accuracy were 0.64, −0.39, and 0.66 for PC1; 0.35, 0.92, and 0.19 for PC2; and −0.68, 0.11, and 0.72 for PC3, with relative sizes and performance directions indicated by arrows in Fig. 2C. These PCs were used as a metric of reading ability in subsequent analyses. In brief (see Discussion for detail), PC1 may reflect general cognitive processes like syntax and memory, PC2 may relate to the conversion of phonology into speech, and PC3 may reflect the balances between letter analysis and broader comprehension, with experienced readers relying more on top-down processing, influencing tasks like transposed-letter detection. None of the PCs showed a statistically significant correlation with participants' age ($r=-0.08$, $p=0.62$ for PC1; $r=-0.18$, $p=0.23$ for PC2; $r=-0.07$, $p=0.64$ for PC3).

Psychophysical thresholds

We also evaluated the degree of individual differences in the psychophysical thresholds (Fig. 3A). The contrast-detection threshold ranged from 1.0% to 4.6% ($M=2.6\%$, $SD=0.8\%$), and the speed-discrimination threshold (Weber fraction) ranged from 0.09 to 0.86 ($M=0.22$, $SD=0.16$), in line with adult data reported by Main et al. (2014). The upper speed limit for object tracking ranged from 0.82 to 1.49 rps ($M=1.19$ rps, $SD=0.14$ rps). No statistically significant correlations were found between the three psychophysical measurements (Fig. 3B; $r=0.20$, $p=0.19$ for contrast detection vs. speed discrimination; $r=-0.04$, $p=0.81$ for speed discrimination vs. object tracking; $r=-0.13$, $p=0.40$ for object tracking vs. contrast detection). Additionally, none of the psychophysical

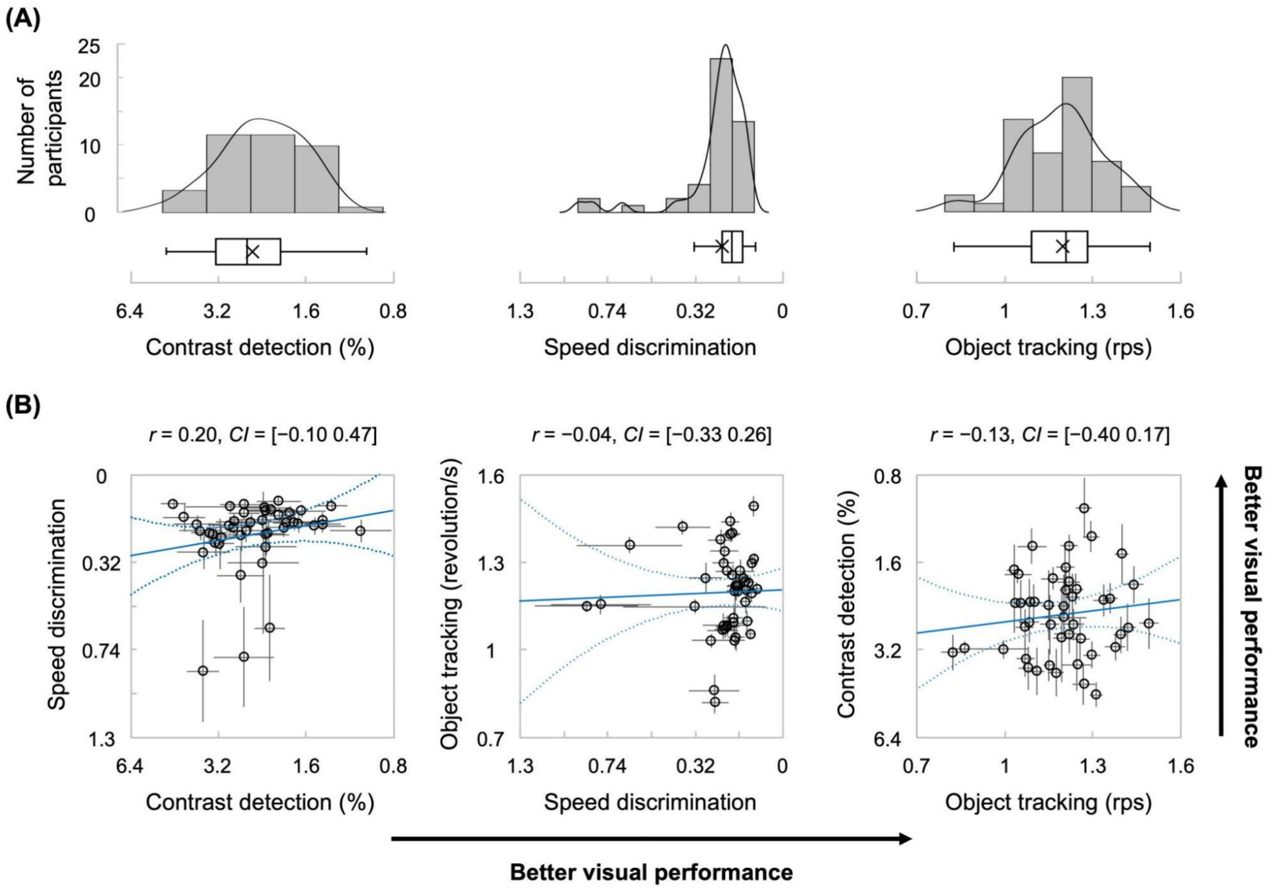

Fig. 3. Psychophysical results. (**A**) Distribution of individual thresholds in all three psychophysical measurements. (**B**) Scatterplot of individual thresholds compared across measurements. Error bars represent ± SEM determined with 10,000 bootstrap iterations. Other conventions are the same as those in Fig. 2A and B.

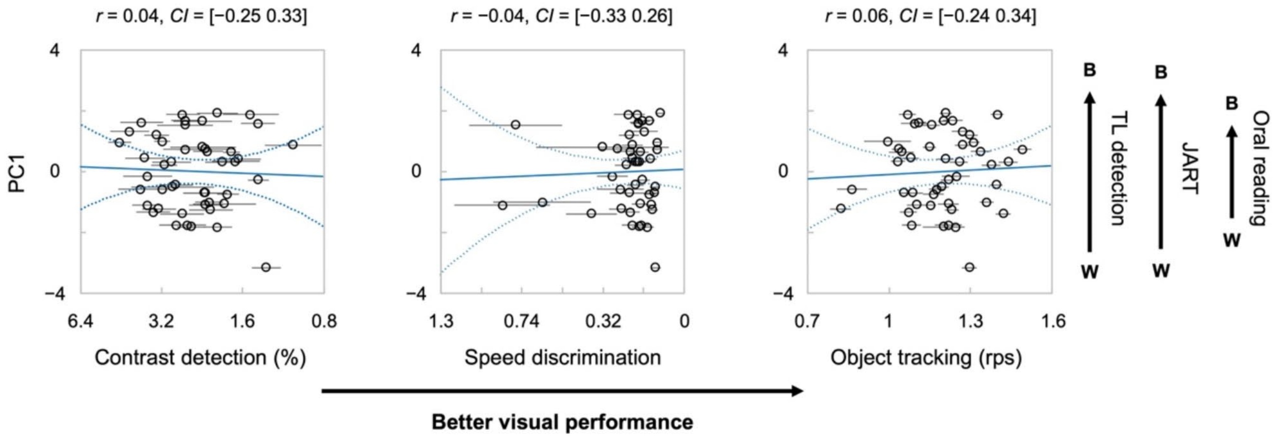

Fig. 4. Individual PC1 scores derived from the reading test scores are plotted as a function of the psychophysical thresholds. Arrows indicate the direction of better performance. Other conventions are the same as those in Fig. 2B and C.

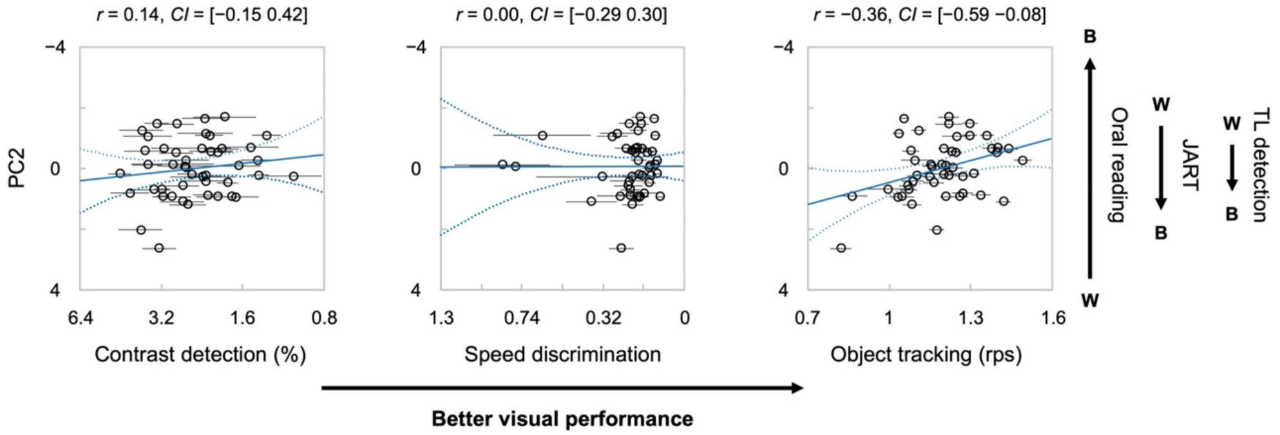

Fig. 5. Individual PC2 scores are plotted as a function of the psychophysical thresholds. The ordinate is inverted to align with the direction of oral reading in the PC coefficient. Other conventions are the same as those in Fig. 4.

measurements showed a statistically significant correlation with participants' age ($r = 0.18$, $p = 0.24$ for contrast detection; $r = -0.03$, $p = 0.85$ for speed discrimination; $r = 0.26$, $p = 0.08$ for object tracking).

Reading ability and psychophysical thresholds correlations

We then compared PC scores with psychophysical thresholds across participants. As shown in Fig. 4, PC1 did not show a statistically significant correlation with the threshold for any psychophysical measurements ($r = 0.04$, $p = 0.79$ for contrast detection; $r = -0.04$, $p = 0.81$ for speed discrimination; $r = 0.06$, $p = 0.72$ for object tracking).

As shown in Fig. 5, PC2 correlated with the speed limit for object tracking (right plot; $r = -0.36$, $p = 0.01$, $r_{\text{Spearman}} = -0.31$) but did not show a statistically significant correlation with the thresholds for contrast detection (left plot; $r = 0.14$, $p = 0.34$) or speed discrimination (middle plot; $r = 0.003$, $p = 0.98$). The partial correlation between PC2 and the speed limit remained moderate after controlling for participants' age ($r_{\text{partial}} = -0.33$). As PC2 had a high coefficient for oral reading time, participants with a higher tracking speed limit tended to read faster orally (see Supplementary Fig. 3 for a scatter plot between the tracking speed limit and oral reading time).

As shown in Fig. 6, PC3 correlated with the speed-discrimination threshold (middle plot; $r = 0.33$, $p = 0.03$, $r_{\text{Spearman}} = 0.30$) but did not show a statistically significant correlation with the thresholds for contrast detection (left plot; $r = 0.17$, $p = 0.26$) or object tracking (right plot; $r = 0.16$, $p = 0.29$). The partial correlation between PC3 and the speed-discrimination threshold remained consistent after controlling for participants' age ($r_{\text{partial}} = 0.33$). As PC3 had a high positive coefficient for transposed-letter detection accuracy and a high negative coefficient for JART-estimated VIQ, participants with better speed discrimination tended to perform better on the JART but worse on transposed-letter detection.

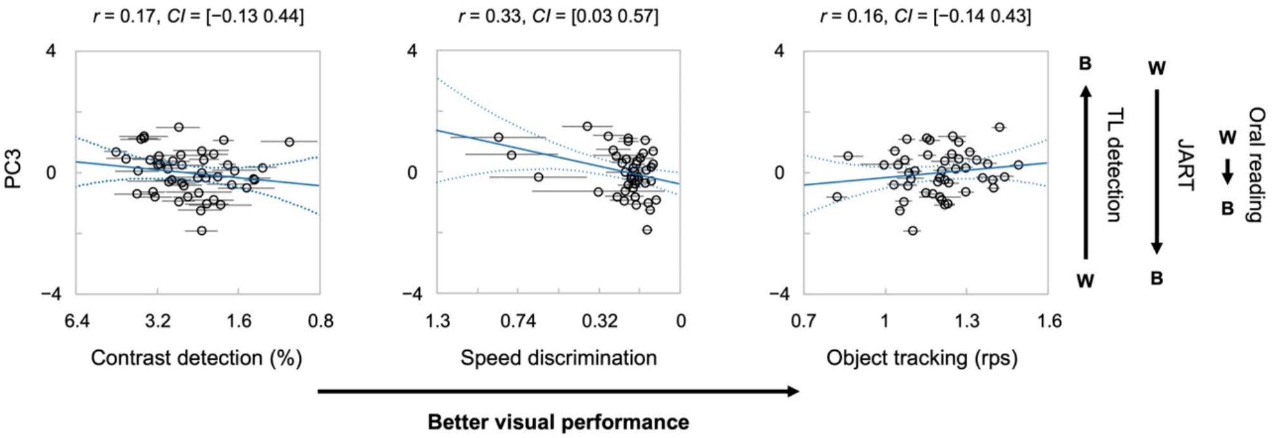

Fig. 6. Individual PC3 scores are plotted as a function of the psychophysical thresholds. Other conventions are the same as those in Fig. 4.

Taken together, these results suggest that different reading components are related to speed discrimination and object tracking. Notably, the correlation with speed discrimination, but the lack of a statistically significant correlation with contrast detection, aligns with findings from previous studies on English readers[35,36].

Discussion

Principal components of Japanese reading performance correlated with psychophysical performance

This study investigated the relationship between reading ability and dynamic visual information processing in Japanese adults. Reading ability was assessed by deriving principal components (PCs) from various reading test scores. Based on the PC coefficients, PC1 showed a dependence on all reading tests, likely reflecting high-level factors such as cognitive, syntactic, and memory-related processes involved in reading tasks. This interpretation is consistent with the present finding that none of the visual functions tested showed a statistically significant correlation with PC1.

PC2 is primarily influenced by oral reading and partially by JART and transposed-letter detection, with the latter two contributing in the opposite direction to oral reading. PC2 may reflect the temporal processing in converting phonological information into pronunciation, possibly involving motor system vocalization. PC3, on the other hand, depends almost equally on JART and transposed-letter detection but in opposite directions, with a smaller contribution from oral reading in the same direction as JART. PC3 may represent a balance between bottom-up letter-by-letter analysis and top-down inferential language processing. A low PC3 score suggests a lower reliance on bottom-up factors and a higher reliance on top-down factors, or possibly a reading style prioritizes abstract general idea acquisition. The contribution of JART may reflect these top-down factors, potentially linked to word familiarity and reading experience.

One might argue why scores of oral reading tests did not significantly correlate with scores of the other two reading tests. It is unlikely that a lack of significant correlation can be explained by limitations in the reliability of measurements, given the fact that each Japanese reading test exhibited a higher degree of reliability. While speculative, one possible interpretation is that Japanese oral reading may involve various processing during reading, not only perceptual and lexical processing but also preparation and execution of vocalization. This complex nature of oral reading might dilute the correlation with other reading tests, which may involve more specific reading aspects.

Relationships with previous studies

Our correlation analyses revealed that PC3 and PC2 correlated with speed discrimination and attentional tracking of multiple moving objects, respectively. These relationships may reflect underlying visual motion and attentional processing. As these PCs did not show a statistically significant correlation with contrast detection, detection sensitivity to the moving grating stimuli would not artificially mediate these relationships. The present results suggest a multifactorial relationship between Japanese reading ability and dynamic visual information processing, similar to what has been argued for English reading ability (e.g.,[31]).

The coefficients of PC2 suggested a relationship between oral reading and attentional tracking. This relationship is consistent with the attention hypothesis of reading ability[16,39]. Temporal processing in parietal cortical areas, such as the IPS[2,3], may serve as a shared mechanism between the sequential conversion of phonological information into pronunciation and the smooth transition of attended positions.

According to the PC3 coefficients, better JART and worse transposed-letter detection may be associated with better speed discrimination. This relationship with low-level motion processing is consistent with the magnocellular hypothesis of reading ability[27] and may suggest the involvement of top-down inferential language processing. Participants with greater reading experience (i.e., word familiarity) may be more inclined to process texts using a top-down approach, relying less on letter-by-letter analysis, which could lead to missing transposed letters. Although the causality is unclear (e.g.,[33]), magnocellular processing may share an underlying mechanism with top-down language processing in Japanese, as suggested by a study on English readers[36].

The correlations found in the present study (~0.33–0.36) are moderate and in a reasonable range from previously reported correlations between English reading ability and speed discrimination or coherent motion sensitivity: for example, 0.19 with samples of 58 children from the same school class in Cornelissen et al.[30], 0.84 with 14 dyslexic and typically developed (DD and TD) children in Demb et al.[35], 0.37 with 14 DD and TD children and 0.52 with 14 DD and TD adults in Main et al.[36], 0.31 with 32 TD children in Talcott et al.[32], and 0.44 with 48 DD and TD children in Joo et al.[33]. These moderate correlations are compatible with the multifactorial nature of the relationship between reading ability and dynamic visual information processing. Since the stimuli and tasks used in our contrast-detection and speed-discrimination experiments were similar to those used by Main et al.[36], visual motion processing may share limiting factors with reading ability in readers of different languages. This is consistent with the magnocellular hypothesis, which suggests independence from language systems.

Limitations

A limitation of the present study is that the test set for Japanese reading ability was not fully standardized. Therefore, we assessed reading ability using principal components rather than raw scores from the test set. Establishing a standardized Japanese reading test battery may be a desirable direction for future research.

The generalizability and universality of our findings are also limited by the sample, which consisted solely of Japanese adults. Whether these results would hold true across different age groups, cultural backgrounds, or language systems remains uncertain. A possible direction is to investigate the relationship between Japanese reading ability and dynamic visual information processing, not only in adults but also in children, to compare it with that of English child readers, and for educational and diagnostic applications. In addition, comparing the correlations of English and Japanese test scores with psychophysical thresholds in Japanese readers learning English may help generalize the relationship between reading ability and dynamic visual information processing across languages.

It should also be confirmed whether the data obtained from online psychophysical experiments are consistent with those obtained in laboratory settings. Such an evaluation can potentially extend this study to a large-scale classroom setting[76]. Given that the observed correlation between PC3 and speed discrimination was moderate ($r = 0.33$), performing future experiments on more extensive and diverse samples using online testing will provide further insights. It would also be promising to investigate how this relationship is related to the microstructural properties of fiber bundles using diffusion-weighted magnetic resonance imaging (e.g.,[73,77,78]).

Conclusions

The present study suggests that the relationship between reading ability and dynamic visual information processing reported by English readers may also hold true for Japanese adults. The present results also found two distinct (orthogonal) reading-related components correlated with speed-discrimination and attentional tracking performance, each of which is consistent with previous hypotheses on the correlation between reading ability and magnocellular and attention functions.

Data availability

All the data and code files are available online on the Figshare public repository (https://doi.org/10.6084/m9.figshare.25377724.v1).

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References

1. Cohen, L. et al. Language-specific tuning of visual cortex? Functional properties of the Visual Word Form Area. *Brain* **125**, 1054–1069 (2002).
2. Wandell, B. A. & Le, R. K. Diagnosing the neural circuitry of reading. *Neuron* **96**, 298–311 (2017).
3. Yeatman, J. D. & White, A. L. Reading: The confluence of vision and language. *Annu. Rev. Vis. Sci.* **7**, 487–517 (2021).
4. Orton, S. T. 'Word-blindness' in school children. *Arch. Neurol. Psychiatry* **14**, 581–615 (1925).
5. Schlaggar, B. L. & McCandliss, B. D. Development of neural systems for reading. *Annu. Rev. Neurosci.* **30**, 475–503 (2007).
6. Adlof, S. & Perfetti, C. A. Individual differences in word learning and reading ability. In *Handbook of Language and Literacy: Development and Disorders* (eds Stone, A. et al.) 246–264 (Guilford, 2013).
7. Bradley, L. & Bryant, P. E. Categorizing sounds and learning to read—A causal connection. *Nature* **301**, 419–421 (1983).
8. Liberman, I. Y. Segmentation of the spoken word and reading acquisition. *Bull. Orton Soc.* **23**, 64–77 (1973).
9. Liberman, I. Y., Shankweiler, D., Fischer, F. W. & Carter, B. Explicit syllable and phoneme segmentation in the young child. *J. Exp. Child Psychol.* **18**, 201–212 (1974).
10. Snowling, M. J. Phonemic deficits in developmental dyslexia. *Psychol. Res.* **43**, 219–234 (1981).
11. Rack, J. P., Snowling, M. J. & Olson, R. K. The nonword reading deficit in developmental dyslexia: A review. *Read Res. Q.* **27**, 28 (1992).
12. Bradley, L. & Bryant, P. E. Difficulties in auditory organisation as a possible cause of reading backwardness. *Nature* **271**, 746–747 (1978).
13. Castles, A. & Coltheart, M. Varieties of developmental dyslexia. *Cognition* **47**, 149–180 (1993).
14. Stein, J. & Walsh, V. To see but not to read; the magnocellular theory of dyslexia. *Trends Neurosci.* **20**, 147–152 (1997).
15. Castles, A. & Coltheart, M. Is there a causal link from phonological awareness to success in learning to read?. *Cognition* **91**, 77–111 (2004).
16. Vidyasagar, T. R. & Pammer, K. Dyslexia: a deficit in visuo-spatial attention, not in phonological processing. *Trends Cogn. Sci.* **14**, 57–63 (2010).

17. Livingstone, M. S., Rosen, G. D., Drislane, F. W. & Galaburda, A. M. Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proc. Natl. Acad. Sci. USA* **88**, 7943–7947 (1991).
18. Lovegrove, W. J., Bowling, A., Badcock, D. & Blackwood, M. Specific reading disability: Differences in contrast sensitivity as a function of spatial frequency. *Science* **1979**(210), 439–440 (1980).
19. Derrington, A. M., Krauskopf, J. & Lennie, P. Chromatic mechanisms in lateral geniculate nucleus of macaque. *J. Physiol.* **357**, 241–265 (1984).
20. Usrey, W. M. & Reid, R. C. Visual physiology of the lateral geniculate nucleus in two species of New World monkey: Saimiri sciureus and Aotus trivirgatis. *J. Physiol.* **523**, 755–769 (2000).
21. Denison, R. N., Vu, A. T., Yacoub, E., Feinberg, D. A. & Silver, M. A. Functional mapping of the magnocellular and parvocellular subdivisions of human LGN. *Neuroimage* **102**, 358–369 (2014).
22. Oishi, H., Takemura, H. & Amano, K. Macromolecular tissue volume mapping of lateral geniculate nucleus subdivisions in living human brains. *Neuroimage* **265**, 119777 (2023).
23. Livingstone, M. S. & Hubel, D. Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science* **1979**(240), 740–749 (1988).
24. Mishkin, M., Ungerleider, L. G. & Macko, K. A. Object vision and spatial vision: Two central pathways. *Trends Neurosci.* **6**, 414–417 (1983).
25. Ram-Tsur, R., Faust, M. & Zivotofsky, A. Z. Sequential processing deficits of reading disabled persons is independent of inter-stimulus interval. *Vision Res.* **46**, 3949–3960 (2006).
26. Skottun, B. C. & Skoyles, J. R. Attention, reading and dyslexia. *Clin. Exp. Optom.* **89**, 241–245 (2006).
27. Boden, C. & Giaschi, D. M-stream deficits and reading-related visual processes in developmental dyslexia. *Psychol. Bull.* **133**, 346–366 (2007).
28. Conlon, E. G., Lilleskaret, G., Wright, C. M. & Stuksrud, A. Why do adults with dyslexia have poor global motion sensitivity?. *Front Hum. Neurosci.* **7**, 1–12 (2013).
29. Cornelissen, P. L., Richardson, A., Mason, A., Fowler, S. & Stein, J. Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. *Vision Res.* **35**, 1483–1494 (1995).
30. Cornelissen, P. L., Hansen, P. C., Hutton, J. L., Evangelinou, V. & Stein, J. F. Magnocellular visual function and children's single word reading. *Vision Res.* **38**, 471–482 (1998).
31. Gori, S., Seitz, A. R., Ronconi, L., Franceschini, S. & Facoetti, A. Multiple causal links between magnocellular-dorsal pathway deficit and developmental dyslexia. *Cerebral Cortex* **26**, 4356–4369 (2016).
32. Talcott, J. B. et al. Dynamic sensory sensitivity and children's word decoding skills. *Proc. Natl. Acad. Sci. USA* **97**, 2952–2957 (2000).
33. Joo, S. J., Donnelly, P. M. & Yeatman, J. D. The causal relationship between dyslexia and motion perception reconsidered. *Sci. Rep.* **7**, 1–7 (2017).
34. Edwards, A. A. & Schatschneider, C. Magnocellular pathway and reading rate: An equivalence test analysis. *Sci. Stud. Read.* **24**, 264–273 (2020).
35. Demb, J. B., Boynton, G. M., Best, M. & Heeger, D. J. Psychophysical evidence for a magnocellular pathway deficit in dyslexia. *Vision Res.* **38**, 1555–1559 (1998).
36. Main, K. L. et al. Speed discrimination predicts word but not pseudo-word reading rate in adults and children. *Brain Lang.* **138**, 27–37 (2014).
37. Facoetti, A. & Turatto, M. Asymmetrical visual fields distribution of attention in dyslexic children: A neuropsychological study. *Neurosci. Lett.* **290**, 216–218 (2000).
38. Iles, J., Walsh, V. & Richardson, A. Visual search performance in dyslexia. *Dyslexia* **6**, 163–177 (2000).
39. Stein, J. The current status of the magnocellular theory of developmental dyslexia. *Neuropsychologia* **130**, 66–77 (2019).
40. Motoyoshi, I. Attentional modulation of temporal contrast sensitivity in human vision. *PLoS ONE* **6**, e19303 (2011).
41. Nakayama, R. & Motoyoshi, I. Sensitivity to acceleration in the human early visual system. *Front. Psychol.* **8**, 1–9 (2017).
42. Jones, M. W., Branigan, H. P. & Kelly, M. L. Visual deficits in developmental dyslexia: relationships between non-linguistic visual tasks and their contribution to components of reading. *Dyslexia* **14**, 95–115 (2008).
43. Wydell, T. N. & Butterworth, B. A case study of an English-Japanese bilingual with monolingual dyslexia. *Cognition* **70**, 273–305 (1999).
44. Tullo, D., Faubert, J. & Bertone, A. The characterization of attention resource capacity and its relationship with fluid reasoning intelligence: A multiple object tracking study. *Intelligence* **69**, 158–168 (2018).
45. Battelli, L., Alvarez, G. A., Carlson, T. & Pascual-Leone, A. The role of the parietal lobe in visual extinction studied with transcranial magnetic stimulation. *J. Cogn. Neurosci.* **21**, 1946–1955 (2009).
46. Culham, J. C., Cavanagh, P. & Kanwisher, N. G. Attention response functions: Characterizing brain areas using fmri activation during parametric variations of attentional load. *Neuron* **32**, 737–745 (2001).
47. Culham, J. C. et al. Cortical fMRI activation produced by attentive tracking of moving targets. *J. Neurophysiol.* **80**, 2656–2670 (1998).
48. Faul, F., Erdfelder, E., Lang, A.-G. & Buchner, A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* **39**, 175–191 (2007).
49. Torgesen, J. K., Wagner, R. & Rashotte, C. TOWRE 2: Test of word reading efficiency 2nd edition. Preprint at (2011).
50. Matsuoka, K., Uno, M., Kasai, K., Koyama, K. & Kim, Y. Estimation of premorbid IQ in individuals with Alzheimer's disease using Japanese ideographic script (Kanji) compound words: Japanese version of National Adult Reading Test. *Psychiatry Clin. Neurosci.* **60**, 332–339 (2006).
51. Nelson, H. E. & O'Connell, A. Dementia: The estimation of premorbid intelligence levels using the new adult reading test. *Cortex* **14**, 234–244 (1978).
52. Nelson, H. E. & Willison, J. R. National Adult Reading Test (NART), 2nd edition. Preprint at (1991).
53. Nelson, H. E. National Adult Reading Test (NART). Preprint at (1982).
54. Perea, M. & Carreiras, M. Do orthotactics and phonology constrain the transposed-letter effect?. *Lang. Cogn. Process* **23**, 69–92 (2008).
55. Frankish, C. & Barnes, L. Lexical and sublexical processes in the perception of transposed-letter anagrams. *Q. J. Exp. Psychol.* **61**, 381–391 (2008).
56. Masserang, K. M. & Pollatsek, A. Transposed letter effects in prefixed words: Implications for morphological decomposition. *J. Cognit. Psychol.* **24**, 476–495 (2012).
57. Perea, M., Nakatani, C. & van Leeuwen, C. Transposition effects in reading Japanese Kana: Are they orthographic in nature?. *Mem. Cognit.* **39**, 700–707 (2011).
58. Perea, M. & Pérez, E. Beyond alphabetic orthographies: The role of form and phonology in transposition effects in Katakana. *Lang. Cogn. Process* **24**, 67–88 (2009).
59. Stites, M. C., Federmeier, K. D. & Christianson, K. Do morphemes matter when reading compound words with transposed letters? Evidence from eye-tracking and event-related potentials. *Lang. Cogn. Neurosci.* **31**, 1299–1319 (2016).
60. Kirkby, J. A., Barrington, R. S., Drieghe, D. & Liversedge, S. P. Parafoveal processing and transposed-letter effects in dyslexic reading. *Dyslexia* **28**, 359–374 (2022).
61. Gakkotosho. Chugakko kokugo 2. Preprint at (2016).
62. Mitsumura Tosho. Kokugo 1. Preprint at (2016).

63. Mitsumura Tosho. Kokugo 2. Preprint at (2016).
64. Sanseido. Gendai no kokugo 1. Preprint at (2016).
65. Schrank, F. A., McGrew, K. S., Mather, N., Wendling, B. J. & LaForte, E. M. Woodcock-Johnson IV tests of achievement. Preprint at (2014).
66. Koeda, T., Terakawa, S. & Shiota, M. Distribution in normal subjects of performance in token test: A basic study for the diagnosis of learning disabilities. *No To Hattatsu* **32**, 25–28 (2000).
67. Brainard, D. H. The psychophysics toolbox. *Spat Vis.* **10**, 433–436 (1997).
68. Pelli, D. G. The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spat. Vis.* **10**, 437–442 (1997).
69. Nakayama, R. & Motoyoshi, I. Vision Toolbox: a programming package of vision science experiments based on Psychtoolbox (in Japanese). *Vision* **30**, 158–165 (2018).
70. Holcombe, A. O. & Chen, W.-Y. Splitting attention reduces temporal resolution from 7 Hz for tracking one object to <3 Hz when tracking three. *J. Vis.* **13**(1), 1–19 (2013).
71. Intriligator, J. & Cavanagh, P. The spatial resolution of visual attention. *Cogn. Psychol.* **43**, 171–216 (2001).
72. Pelli, D. G. & Tillman, K. A. The uncrowded window of object recognition. *Nat. Neurosci.* **11**, 1129–1135 (2008).
73. Huber, E., Donnelly, P. M., Rokem, A. & Yeatman, J. D. Rapid and widespread white matter plasticity during an intensive reading intervention. *Nat. Commun.* **9**, 1–13 (2018).
74. JASP Team. JASP(Version 0.17.2) [Software]. Preprint at https://jasp-stats.org/ (2023).
75. Benjamini, Y. & Hochberg, Y. Controlling the false discovery rate: A practical and powerful approach to multiple testing. *J. R. Stat. Soc. Ser. B Stat. Methodol.* **57**, 289–300 (1995).
76. Yeatman, J. D. et al. Rapid online assessment of reading ability. *Sci. Rep.* **11**, 1–11 (2021).
77. Dougherty, R. F. et al. Temporal-callosal pathway diffusivity predicts phonological skills in children. *Proc. Natl. Acad. Sci. USA* **104**, 8556–8561 (2007).
78. Yeatman, J. D. et al. Anatomical properties of the arcuate fasciculus predict phonological and reading skills in children. *J. Cogn. Neurosci.* **23**, 3304–3317 (2011).

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Author contributions

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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