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RESEARCH PAPER

Spaces or colors? The role of marking word boundaries on reading aloud in Javanese script

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Abstract Prior research in Chinese, a logographic unspaced writing system, has shown that visual cues to mark word boundaries (e.g., inserting interword spaces and coloring alternate words) can facilitate reading, particularly for developing readers. The present series of experiments examines the effectiveness of these two visual cues for word boundaries (spaces, colors) when reading aloud in Javanese script, an alpha-syllabic unspaced writing system used in some regions of Indonesia. In Experiments 1 and 2, developing and adult readers read aloud texts in standard unspaced format or with interword spaces. In Experiments 3 and 4, developing and adult readers read aloud unspaced alternating-color and mono-color texts. Finally, Experiment 5 directly compared the effectiveness of the word segmentation cues (interword spaces, colors) on adult skilled readers within the same experiment. Results showed that developing readers benefited from both types of word segmentation cues. For adult readers, only the insertion of interword spaces facilitated reading aloud. Thus, inserting interword spaces in Javanese script is generally a more effective word segmentation cue than coloring alternate colors.

Keywords Reading · Javanese · Word boundaries · Interword spacing · Color information

The ability to read is an essential skill for both social and educational advancement in contemporary society. Although reading involves multiple processes, one of its key elements is word identification (e.g., lexical quality hypothesis: Perfetti & Hart, 2002; simple view of reading: Hoover & Gough, 1990). Another critical component in the reading flow is dividing a sequence of letters (or characters) into distinct words. This last step is essential for word recognition and reading efficiency (Li & Pollatsek, 2020; Li et al., 2009; Torres-Díaz et al., 2020).

In most writing systems (e.g., Latin-based orthographies, Cyrillic-based orthographies, Arabic-based orthographies, Hangul orthography), segmenting words is straightforward: consecutive words are separated by some extra space—as in the current paper. It has been repeatedly argued that these interword spaces are essential to guide the readers' eye movements through continuous text (i.e., landing closer to the center of the words [optimal viewing position]; Pollatsek & Rayner, 1982; Rayner et al.,

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2013). Indeed, a large number of experiments have consistently shown that removing interword spaces in these orthographies disrupts reading: readers make shorter saccades, longer fixations, and more regressions when reading unspaced than spaced text (e.g., Baek et al., 2023; Degno et al., 2019; Drieghe et al., 2017; Hermena, 2021; McGowan et al., 2014; Perea & Acha, 2009; Rayner et al., 1998, 2013; Veldre et al., 2017).

Interestingly, in some Asian writing systems (e.g., Chinese, Japanese, Lao, Khmer, Thai, Balinese, Javanese, Sundanese, and Burmese), texts are written without explicit demarcation of word boundaries. As a historical note, Latin was also initially written without interword spaces (i.e., *scriptio continua*); interword spaces were added in the Middle Ages (see Saenger, 1997, for an overview). Thus, one important research question is whether adding visual cues marking word boundaries to unspaced writing systems provides faster reading than the standard unspaced text in adult and developing readers. We first review the most investigated word boundary cue for unspaced writing systems: inserting interword spaces. Then, we review the impact of a less studied visual cue, alternating colors across successive words (e.g., thisisanexample). Afterward, we will introduce the rationale of the experiments conducted in an overlooked, unspaced writing system, Javanese.

Adding interword spaces in unspaced writing systems

With adult skilled Chinese readers, a logographic unspaced writing system, Bai et al. (2008) examined whether adding interword spaces increased reading speed in Chinese. They measured the participants' eye movements when reading standard unspaced sentences and sentences with added interword spaces. They found no overall difference in reading performance between these two conditions, suggesting that inserting spaces between words does not produce an advantage in Chinese adult readers. Bai et al. argued that the null effect of inserting interword spaces might result from trade-offs due to the facilitation in word segmentation but disruption from format unfamiliarity. This interpretation was supported by evidence from Zang et al., (2013; see also Chen et al., 2021a, 2021b; Li et al., 2022a, 2022b; Ma et al., 2019). For example, Zang et al. (2013) found that, while the overall reading speed was similar in spaced and unspaced sentences, interword spaces reduced participants' first-pass fixation durations and refixation probability of an embedded target word, suggesting that interword spaces did facilitate word identification in Chinese. Furthermore, when reading complex and unfamiliar texts in Chinese, reading speed is faster for spaced than unspaced sentences (2000b; Hsu & Huang, 2000a), probably due to the difficulty of identifying the boundaries of unfamiliar words.

A somewhat similar pattern occurs in Japanese, another unspaced writing system. Unlike Chinese, Japanese contains not only Kanji characters—ideograms similar to Chinese—but also letters from two syllabaries (Hiragana, Katakana) that are visually simpler than Kanji characters. Sainio et al. (2007) conducted an eye movement experiment with adult readers in which participants read sentences containing both Kanji and Hiragana (i.e., the usual scenario in Japanese, e.g., 成田空港の経営は現状ではお世) or sentences containing only Hiragana words (e.g., なりたくうこうのけいえいはげ). In addition, the sentences were presented in the standard unspaced format or with interword spaces. For the sentences containing only Hiragana words, overall reading times were faster, and forward saccade length was longer when interword spaces were inserted, suggesting that these spaces help the word segmentation process. Critically, for the sentences with the typical Japanese format (i.e., containing both Kanji and Hiragana words), there were no differences in the unspaced and spaced sentences—note that visual differences between Kanji and Hiragana characters can serve as a word segmentation cue.

The issue of adding interword spaces has also been studied in alphabetic unspaced writing systems such as Thai. In an eye movement study in Thai, participants read sentences with target words embedded in sentences with or without interword spaces (Winskel et al., 2009). Results showed longer gaze durations and total time fixations on target words in unspaced

than spaced sentences. Notably, the distribution of initial landing positions on target words or the initial fixation duration was not influenced by the layout of sentences. Winskel et al. (2009) concluded that adding interword spaces in Thai helps word processing but not word targeting or early lexical segmentation (see also Winskel et al., 2012).

All in all, these findings reveal that adult skilled readers in unspaced logographic systems do not seem to have a sizable benefit from the addition of interword spaces (e.g., Chinese or Japanese sentences composed of Kanji and Hiragana); however, there may be some facilitation when reading alphabetic orthographies (e.g., Thai) and, under some circumstances in Chinese (e.g., with texts containing infrequent words) and Japanese (e.g., Hiragana-only sentences). As the many years of expertise with unspaced writing systems may make participants highly proficient at segmenting words in these scripts, it is crucial to examine the use of visual cues in less skilled, developing (or L2) readers.

Prior research in Chinese has consistently found a benefit of inserting spaces in developing readers (Blythe et al., 2012; Chen et al., 2021a, 2021b; Li et al., 2022a, 2022b; Liang et al., 2015; Wang, 2015). For example, Blythe et al. (2012) found that interword spacing benefited children in learning to read new Chinese vocabulary, reflected in shorter reading times and fewer refixation and backward regressions. More recently, Li et al., (2022a, 2022b) observed a facilitative effect of adding interword spacing on Chinese first graders' reading speed, reducing this advantage for higher graders (Grades 2 & 3). Likewise, the addition of interword spacing helps reading Chinese sentences for second-language learners. This is the case when L1 is a Latin-based alphabet (Bai et al., 2013; Chen et al., 2021a, 2021b; Cui, 2023; Shen et al., 2012) and also when L1 is another Asian language (e.g., Japanese, Korean, and Thai: Shen et al., 2012).

Using colors to mark word boundaries in unspaced writing systems

Another visual cue to help reading in unspaced orthographies is using alternating colors across successive words (Pan et al., 2020; Perea & Wang, 2017; Zhou et al., 2018). An advantage of this cue is that, unlike interword spaces, it does not alter the overall layout of the texts. The logic of this manipulation is that the characters with the same colors would be perceived as a group (see De Simone et al., 2023; Goldfarb & Treisman, 2011; Treisman & Gelade, 1980) and, therefore, can serve to mark word boundaries during reading (see Perea et al., 2015; Pinna & Deiana, 2018).

In the initial implementation of this manipulation in an unspaced script (Chinese), Perea and Wang (2017) asked participants to read aloud two versions of texts: one containing mono-color words (e.g., 大象打算在森林开一家商店) and the other with alternating colors across words (e.g., 大象打算在森林开一家商店, *The elephant/ plans to/ in/ the forest/ open/ a/ shop*). They found that developing readers read faster when different colors segmented words in texts. This effect also occurred with adult readers, but only when the texts contained unfamiliar words. To examine the locus of the effects in a silent reading scenario in adult readers, Zhou et al. (2018) presented sentences with uniform color (e.g., 近来动物园首次对孔雀成功进行了人工繁殖) and with alternating-color words (e.g., 近来动物园首次对孔雀成功进行了人工繁殖 [*The zoo/ recently/ successfully/ conducted/ artificial/ propagation/ to peacocks/ for the first time*]) while registering the participant's eye movement. Compared to the mono-color baseline, demarcating word boundary with color information shifted fixation locations closer to the word center, and readers were less likely to refixate a word for the alternating-color sentences. Thus, these findings suggest that color information helps lexical processing and saccade targeting.

Similar to the case of inserting interword spaces, the benefit of using alternating colors to mark word boundaries is magnified for developing readers. Following the research of Perea and Wang (2017), Song et al. (2021) tracked the developmental trajectory of the role of color-based word boundary cues for Chinese children (aged 7–10 years) when reading aloud sentences. They found faster reading speed in the alternating-color condition for children in Grades 2 and 3. However, such facilitation was not observed in Grades 4 and 5 children. Similarly, an advantage of alternating color sentences over unspaced mono-color sentences during sentence reading has also been reported with Korean students learning Chinese

(Zhou et al., 2020) and with deaf and hard-of-hearing children (Grades 4–6) learning Chinese (Yan et al., 2019).

Thus, the alternating color manipulation benefits reading an unspaced writing system such as Chinese, especially for developing and L2 readers. However, to our knowledge, this manipulation has not yet been tested in other unspaced writing systems.

The rationale of the experiments

Previous studies that examined whether visual cues help reading in unspaced writing systems focused either on the insertion of interword spaces or on the alternating coloring of successive words, thus making the direct comparison difficult. To our knowledge, only one study has compared the effectiveness of inserting interword spacing *versus* adding color alternation. In an experiment conducted with Chinese adult readers, Ma et al. (2019) registered the readers' eye movements while reading sentences. These conditions included a standard unspaced condition, an alternating color condition (e.g., 我们的初中教育应该跳出升学教育的思想框架 *Our high school education should not only aim to go to college*) and a condition with inserted interword spaces (e.g., 我们 的 初中 教育 应该 跳出 升学 教育 的 思想 框 架-). Neither visual cue provided a benefit regarding overall reading speed relative to the standard unspaced format for adult skilled Chinese readers. However, one should be cautious about generalizing these null effects to other populations (e.g., developing readers, L2 readers) or other unspaced (non-logographic) writing systems.

In the present series of experiments, we examined whether marking word boundaries helped reading aloud text in an unspaced script, Javanese, and which visual cue is the most effective. We did so by inserting spaces between words or alternating colors across words. As reviewed earlier, and following Gestalt laws (Wertheimer, 1938), both proximity (space) information and bottom-up similarity (color) could serve as efficient visual cues for object organization (Ma et al., 2019). These salient perceptual features would presumably ease readers from the ambiguity in identifying which word a given letter belongs to (see Winskel, 2017) and may facilitate word reading.

The Javanese script, also known as Akshara Jawa, is primarily used to write the Javanese language, an Austronesian and regional language in Indonesia. This script has also been used to write other local languages in Indonesia (e.g., Sundanese, Madurese, and Sasak; Behrend, 1996). Javanese script was actively used for writing until the mid-twentieth century before the influence of Indonesian (or *Bahasa Indonesia*, the official language) gradually replaced its function in the educational system. In contemporary usage, the Javanese written form of some local and official languages is frequently seen on public signage. Javanese script is taught as part of the local curriculum at the primary and secondary education levels in several regions of Java and nearby islands (e.g., Madura, Bali, and Lombok). Note, however, that the school language in Indonesia is Indonesian, which originated from Malay and is written in Latin script with interword spaces.

Javanese script uses an alpha-syllabic alphabet (Comrie, 2009) containing 20 to 33 basic letters (see Fig. 1). Each letter, or *aksara*, stands for a syllable and has an inherent vowel, which can be modified by adding diacritics that appear around the main letter. For closed syllables in the middle of words or sentences, a conjunct form called *pasangan* is used to eliminate the inherent vowel of the letter before it. Furthermore, each basic letter has its own *pasangan* counterpart. For example, in "ꦠꦶꦢꦏ꧀ꦲꦢ" (tidak ada; *nothing*), the word "tidak", which ends with the consonant /k/, derives from tidaka (ꦠꦶꦢꦏ). In this case, the *pasangan* counterpart (◌꧀ꦲ) replaces the letter "ꦲ"(a) in the following word "ada" to nullify the inherent vowel /a/ in the letter "ꦏ"(ka). The result of the letters "ꦢꦏ꧀ꦲ"(da-ka- *pasangan*) is the closed syllable [dak].

With these unique complex characteristics of the Javanese script and being studied only as part of the local curriculum, readers often find it challenging to acquire fluency when reading and writing in this script (Avianto & Prasida, 2018). On top of that, words in Javanese script are not separated by spaces, making it challenging to locate the word boundaries —note that words may consist of either one (e.g., ꦢꦶ [di] *in*), two (e.g., ꦏꦠ [kata] *word*); and more letters (e.g., ꦩꦼꦤ꧀ꦗꦢꦶ [menjadi] *become*). However, no research has been done examining the effects of word boundary information in reading Javanese script,

which, besides its theoretical implications, would also provide practical implications for learning this script.

We designed five experiments to answer two research questions: (1) whether developing and adult readers of Javanese script benefit from visual cues to segment words, and (2) which of the visual cues for word boundaries (insertion of interword spaces *versus* color alternation) is more effective for readers of Javanese script. Experiments 1 (developing readers) and 2 (adult readers) examined the role of inserting interword spacing on reading-aloud performance in Javanese script. Experiments 3 and 4 examined the role of color cues (alternating color vs. mono-color) in developing and adult readers, respectively. Finally, in Experiment 5, we directly compared the benefit of inserting interword spacing *versus* using alternating colors across words with adult readers.

One issue that needs to be considered in the present experiments is that all readers are familiar with Indonesian, a spaced Latin-based script with interword spaces. While Javanese readers begin learning the Javanese script in primary school, reading in this script is often restricted to classroom practice (Yulianto et al., 2023). This scenario results in relatively low levels of reading ability in Javanese script (Setiawan, 2013). As a result, we expect the benefit of visual cues to mark word boundaries to occur in developing and adult readers. Furthermore, as all participants are used to reading in an orthography with interword spaces (Indonesian), these spaces may be more effective than alternating colors in Javanese. This situation differs from Chinese or Thai, where interword spaces are only encountered in foreign languages (e.g., English).

Experiment 1 (Effects of interword space in developing readers)

Method

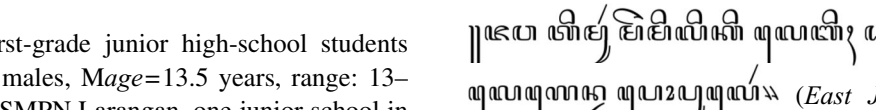
Participants

Twenty-four first-grade junior high-school students (22 females, 2 males, M*age*=13.5 years, range: 13–14 years) from SMPN Larangan, one junior school in Madura (Indonesia), participated voluntarily in the experiment. All participants were native Indonesian speakers/readers and learned Javanese script in primary school. They were introduced to Javanese script from 1st to 3rd grades and began learning to read and write in this script from 4th grade in primary school. Thus, the participants' experience with reading this script was four years on average. All participants had normal (or corrected) vision, and none were color-blind. This sample size, the same in all the experiments, was the same used in the Perea and Wang (2017) experiments. Informed consent was obtained from the participants' parents. The experiments reported in this study were approved by the Ethics Committee for Experimental Research at the University of Valencia, and followed the criteria of the Helsinki Declaration.

Materials and design

Two text passages were selected from https://folkloreforkids.blogspot.com/, and they are available at https://osf.io/9x2d6/?view_only=03fcb580d3044ade86835b6213804df8. The texts were in Indonesian language and written in Javanese script. Text A was about the legend of Surabaya; Text B was about the legend of Banyuwangi. We did not choose passages from textbooks to avoid the influence of the familiarity of the content. Text A contained 440 characters (185 words) and 27 punctuation marks; Text B contained 423 (187 words) and 32 punctuation marks. An additional sample of twenty junior school students who did not participate in the reading-aloud experiment evaluated the difficulty of the two texts separately on a 1 to 7 Likert scale (1=very easy, 7=very difficult). The data showed similar scores for Text A (mean=5.05, *SD*=0.76) and Text B (mean=5.10, *SD*=1.02), $t_{(19)}$=-0.271, p=0.789. Each text, approximately 20–21 lines, was presented in black in Javanese Text 14-pt font on a computer screen with a white background.

The independent variable was interword spacing (spaced text vs. standard [unspaced] text). In the spaced text, spaces were inserted between words as in the sentence



(*East Java has more than one popular legend*). The dependent variable was the number of words per minute—we also

Fig. 1 Illustration of basic characters in the Javanese script with the inherent vowel a and Latin transliterations (in blue)

collected the participant's reading comprehension scores.

For half of the participants, Text A was written with interword spaces, and Text B was presented in the standard unspaced format, whereas for the other half, Text A was written in the standard format, and Text B was written with interword spaces. The order of presentation of both texts was counterbalanced across participants. Participants were randomly assigned to one of the counterbalancing conditions.

Procedure

The experiment was conducted in a silent room using a computer equipped with DMDX (Forster & Forster, 2003) to present the texts and record participants' responses. Participants first viewed an instruction

page with examples of the text formats used in the experiment, displayed in the same location as the experimental texts to familiarize them with the task. Texts were presented one at a time in random order across participants. Participants were instructed to read each text aloud while trying to comprehend it. The total reading time for each text was recorded in seconds and converted into words per minute (i.e., reading speed). After each text, the teacher or experimenter pressed the button to proceed to a question page, where participants orally answered two yes/no comprehension questions about the text. This setup allowed children to focus solely on reading and answering questions.

Results and discussion

The number of words per minute (wpm) per condition is presented in Table 1. Comprehension scores were quite high (91.7% and 87.5%) for the spaced and standard unspaced texts, indicating that participants understood the texts reasonably well.

We conducted a paired *t-test* on the participants' reading speed (in word per minute, wpm) as a function of spacing (spaced vs. [standard] unspaced text). Results showed that participants read spaced text faster than standard text (38.1 vs. 33.4 wpm, respectively), $t_{(23)}=4.509$, $p < 0.001$, with a medium effect size (Cohen's d=0.47).

Thus, adding interword spaces to texts in Javanese script speeded reading aloud for developing readers relative to the standard unspaced format. This finding is consistent with previous findings with native developing readers of Chinese (Blythe et al., 2012; Li et al., 2022a, 2022b) and non-native learners of Chinese (e.g., Chen et al., 2021a, 2021b; Cui, 2023; Shen et al., 2012).

The question in Experiment 2 is whether skilled adult readers, who have better quality representation for words and higher word segmentation efficiency, still show a facilitative effect in reading Javanese script due to the addition of interword spaces. As indicated earlier, in Chinese, the benefit, in terms of overall reading speed, of inserting interword spaces that occurs with developing readers of Chinese (e.g., Shen et al., 2012) tends to disappear in skilled readers (e.g., Bai et al., 2008). At the same time, as indicated earlier, the scenario of Javanese script is different from Chinese: All readers in the present experiments are also fluent in Indonesian (a spaced Latin-based orthography, which is the language of instruction). As such, interword spaces may also help segment words when reading in Javanese script.

Experiment 2 (Effects of interword space in adult readers)

Method

Participants

Twenty-four adult readers (15 females, 9 males, *Mage*=24.3 years, range: 18–35 years) voluntarily participated in the experiment. They were teachers or college students from the University of Muhammadiyah Malang in Central Java (Indonesia). Participants had been introduced to the Javanese script around grade 3 (ages 8–9), with their experience with the script ranging from 10 to 25 years. Some participants had majored in the Javanese language. All were native Indonesian speakers/readers with normal or corrected-to-normal vision, and none were color-blind. Informed consent was obtained from all participants prior to the experiment.

Materials and design

Two text passages were selected from the same source as Experiment 1 (they are available at https://osf.io/9x2d6/?view_only=03fcb580d3044ade86835b

Table 1 Reading speed (number of words per minute) in Experiments 1 and 2

	Spaced	Standard (unspaced)
Developing readers (Exp. 1)	38.1 (2.05)	33.4 (2.01)
Adult readers (Exp. 2)	77.4 (2.87)	71.9 (2.82)

Standard errors are given in the parentheses

6213804df8). Text C was about the legend of a dizzy swamp, and Text D was about the legend of a three-colored lake. Text C had 448 letters (185 words) and 40 punctuation marks; in Text D, there were 415 letters (176 words) and 39 punctuation marks. A sample of 11 adult readers, who did not participate in the reading-aloud experiment, evaluated the difficulty of the two texts separately on a 7-point Likert scale (1 =very easy, 7=very difficult). A paired *t-test* showed is no significant difference in perceived difficulty between Text C (mean=3.45, *SD*=0.82) and Text D (mean=3.64, *SD*=0.67), $t_{(10)}$=-0.803, p=0.441.

Procedure

The procedure was the same as in Experiment 1, except that the participants themselves pressed the buttons to proceed through the tasks. After reviewing the instruction page with examples of the text formats, participants pressed a button to begin each text. Upon finishing a text, they pressed another button to move to the question page, where they orally answered two yes/no comprehension questions.

Results and discussion

The number of words per minute per condition is displayed in Table 1. Accuracy in the comprehension questions was at ceiling level (97.9% in both the spaced and standard texts).

As with Experiment 1, we conducted a paired *t-test* on participants' reading speed as a function of spacing format. Javanese adult readers showed significantly faster reading speeds for spaced text compared to standard unspaced text, $t_{(23)}$=2.203, p =0.038, d=0.39 (77.4 vs. 71.9 wpm, respectively).

Thus, adult skilled readers of Javanese script also benefited from the presence of interword spaces. As indicated earlier, a potential reason why the benefit of adding interword spaces applies to adult readers when reading in Javanese script is they are all speakers and readers of Indonesian and, thereby, highly familiar with spaces marking word boundaries.

The question now is whether there is a reading benefit when reading aloud Javanese script with the use of another visual cue to segment words: alternating color across successive words. This is the goal of Experiment 3 (developing readers) and Experiment 4 (adult readers).

Experiment 3 (Effects of alternating colors in developing readers)

Method

Participants

Twenty-four 1st-grade junior high school students (20 females, 4 males, *Mage*=13.6 years, range: 13–14 years) from SMP 2 Pandaan Junior School in East Java (Indonesia) participated voluntarily in the experiment. They were native Indonesian speakers/readers and learners of Javanese script. As in Experiment 1, the participants' experience with Javanese reading was four years on average. They had normal (or corrected) vision, and none was color-blind. Informed consent was obtained from the participants' parents before the experiment.

Materials and design

The independent variable was color information (alternating-color text vs. mono-color text). As in Experiments 1–2, the dependent variable was the number of words per minute—we also collected a reading comprehension score.

We used the same texts as in Experiment 1 (they are available at https://osf.io/9x2d6/?view_only=03fcb580d3044ade86835b6213804df8). To color the texts, we employed the same four equiluminant colors as in the Perea and Wang (2017) experiments (red [CIE chromaticity coordinates x, y=0.55, 0.37; RGB 171, 41, 51], green [0.34, 0.51; 78, 167, 55], brown [0.49, 0.40; 178, 112, 49], and blue [0.17, 0.19; 53, 85, 142]). The mono-color texts were presented in red, green, brown, or blue (25% in each case). For the alternating-color texts, the color of the words alternated between red, green, brown, and blue (e.g., as in the sentence ). The texts were presented in Javanese Text 14-pt font on a computer screen with a black background.

For half of the participants, Text A was presented in an alternating-color format, and Text B in a mono-color format. For the other half, the formatting was

the inverse. The order of presentation of the texts was counterbalanced across participants. Participants were randomly assigned to each of the counterbalancing conditions.

Procedure

The procedure was the same as in Experiment 1, except for using colors as boundary cues instead of interword spaces.

Results and discussion

The number of words per minute per condition is displayed in Table 2. Comprehension scores were at ceiling level (97.9% vs. 95.8% for alternating-color and mono-color texts, respectively).

We conducted a paired *t-test* on the participants' reading speed (in wpm) as a function of text format (alternating-color vs. mono-color). Participants read alternating-color text significantly faster than mono-color text (47.3 vs. 45.5 wpm, respectively), $t_{(23)}$= 2.34, p=0.028, d=0.21.

The present experiment, conducted with developing readers in Javanese script, showed faster reading times in alternating colors than mono-color texts. This finding generalizes to Javanese scripts previous findings obtained with developing readers in Chinese (Pan et al., 2020; Perea & Wang, 2017; Song et al., 2021), and L2 readers of Chinese (Zhou et al., 2020).

The question in Experiment 4 is whether the benefit of the alternating-color text also occurs with adult skilled readers.

Experiment 4 (Effects of alternating colors in adult readers)

Method

Participants

There were the same 24 participants as in Experiment 2.

Materials and design

The experimental design was the same as Experiment 3. Two text passages were the revised version of texts A and B from Experiment 1. They were adjusted by replacing some words with their synonyms or adding affixes to make the texts more difficult. They are available at https://osf.io/9x2d6/?view_only=03fcb580d3044ade86835b6213804df8. Text E contained 484 letters (or 187 words) and 31 punctuation marks; in Text F, there were 487 letters (or 189 words) and 31 punctuation marks. Eleven adult readers who did not participate in the reading-aloud experiment were asked to evaluate the difficulty of the two texts separately on a 1 to 7 Likert scale (1= very easy, 7=very difficult). Both texts were matched in difficulty: Text E (mean=3.36, SD=0.81) and Text F (mean=3.36, SD=0.92), $t_{(10)} < 0.1$, $p > 0.9$.

Procedure

It was the same as Experiment 3.

Results and discussion

The number of words per minute per condition is displayed in Table 2. Comprehension scores were very high (93.8% and 97.9% for alternating-color and mono-color texts, respectively).

A paired t-test on participants' reading speed as a function of color format showed no evidence of a

Table 2 Reading speed (number of words per minute) in Experiments 3 and 4

	Alternating color	Standard (Mono-color)
Developing readers (Exp. 3)	47.3 (1.72)	45.5 (1.74)
Adult readers (Exp. 4)	77.5 (3.41)	75.9 (3.86)

Standard errors are given in the parentheses

difference in Javanese readers' performance between alternating-color and mono-color texts (77.5 vs. 75.9 wpm, respectively), $t_{(23)}$=0.862, p=0.398, d=0.09.

This experiment showed a comparable reading speed in Javanese script for alternating color and mono-color texts with adult readers. This outcome is consistent with the idea that skilled adult readers may find it unnecessary to use visual cues such as color to mark word boundaries in unspaced orthographies (e.g., Perea & Wang, 2017). Notably, these same participants showed a reading benefit from inserting interword spaces in Experiment 2, suggesting that interword spaces may be a more effective word segmentation cue. However, while of comparable difficulty, the texts used in Experiments 2 and 4 were different. To directly address the comparison of how effective are these two visual cues (interword spaces vs. colors) in adult readers of Javanese script, we designed a new experiment. Experiment 5 included the spaced condition, the alternating-color condition, and the unspaced mono-color condition as a baseline with the same group of participants.

Experiment 5 (Adding spaces vs. colors as visual cues in adult readers)

Method

Participants

Twenty-four adult readers (16 females, 8 males, *Mage*=23.7 years, range: 19–35 years) voluntarily participated in the experiment. Similar to the adult readers in Experiments 2 and 4, adult readers in Experiment 5 were college teachers or students, with three of them being staff who had learned Javanese from elementary to high school. All were native speakers of Indonesian. Their experience with Javanese scripts ranged from 10 to 25 years. All participants had normal (or corrected-to-normal) vision, and none were color-blind. Informed consent was obtained from all participants.

Materials and design

The independent variable was the Type of format, with three levels (spaced mono-color condition, unspaced alternating-color condition, and unspaced mono-color condition). The main dependent variable was the number of words per minute.

Three texts were adapted from Text C, E, and F with minor modifications (i.e., the titles were deleted; they are available at https://osf.io/9x2d6/?view_only=03fcb580d3044ade86835b6213804df8). We then relabeled them as Text G (478 letters or 185 words; mean=3.45, SD=0.82), Text H (483 letters or 188 words; mean=3.36, SD=0.81), and Text I (444 letters or 183 words; mean=3.36, SD=0.92). One-way Analyses of Variance (ANOVA) on text difficulty suggested no evidence of a difference among the three texts, F(2, 32)=0.04, p=0.959. Each text was presented in Javanese Text 14-pt font on a computer screen with a black background. Following a Latin Square design, the three experimental conditions were rotated across three texts. For the spaced/unspaced mono-color condition, texts were equally presented in red, green, brown, or blue. The order of presentation of the three texts was counterbalanced across participants.

Procedure

It was parallel to Experiments 2 and 4.

Results and discussion

The number of words per minute for each condition is displayed in Table 3. Comprehension scores were near ceiling (95.8%, 100%, and 100% for spaced mono-color texts, unspaced alternating-color texts, and unspaced mono-color conditions, respectively).

The ANOVA on reading speed (wpm) showed a significant effect of Format, F(2, 46)=6.62, p=0.003. Holm-Bonferroni-corrected t-tests revealed that (1) reading was faster for spaced mono-color texts compared to unspaced mono-color texts (74.4 vs. 68.4 wpm), t(23)=3.43, p=0.004, d=0.70, and alternating-color texts, t(23)=2.77, p=0.016, d=0.57; and (2) there was no evidence of an effect of alternating color, as reading speed for alternating-color and unspaced mono-color texts was similar (69.6 vs. 68.4 wpm), t(23)=0.66, p=0.52, d=0.12.

This experiment replicated the pattern obtained in Experiments 2 and 4, using the same participants and reading materials: For adult skilled readers, interword spacing is an effective segmentation cue that helps

Table 3 Reading speed (number of words per minute) in Experiment 5

Spaced (Mono-color)	(Unspaced) Alternating color	Standard (Mono-color)
74.4 (2.93)	69.6 (2.77)	68.4 (2.37)

Standard errors are given in the parentheses

reading aloud text in Javanese script, whereas alternating color is not.

General discussion

Javanese script is an alpha-syllabic, unspaced writing system used mainly in Java (Indonesia) and other nearby islands that has been neglected in the mainstream literature on visual word recognition and reading. We designed five experiments that examined the impact of two visual cues designed to help word segmentation (inserting spaces and alternating colors across words) in reading aloud texts. In Experiments 1 and 2, participants read aloud Javanese texts in standard unspaced format or with interword spaces. Developing (Experiment 1) and adult readers (Experiment 2) read the texts with interword spaces faster than those in the standard unspaced format. The design of Experiments 3 and 4 followed the same logic, except that we compared a condition composed of alternating-color unspaced texts (where each successive letter was in a different color) and standard, unspaced mono-color texts. Results showed an advantage in reading aloud for the alternating-color texts for developing readers (Experiment 3) but not for adult readers (Experiment 4). Finally, in Experiment 5, we directly compared the effectiveness of the two segmentation cues on adult readers, with the mono-color unspaced text as a baseline. Results again showed the benefit of the texts with interword spaces over the unspaced texts, whereas alternating-color texts did not produce an advantage over the standard mono-color texts. Taken together, these findings reveal that inserting interword spaces is a more effective visual cue to reading aloud Javanese script than using alternating colors. In the following paragraphs, we discuss the implications of these findings.

The more effective visual cue for word segmentation in Javanese script was the insertion of interword spaces: it helped developing readers and adult readers. This latter outcome is apparently at odds with the findings from other unspaced writing systems (e.g., Chinese), where the addition of interword spacing only plays a minimal role in skilled adult readers. Nonetheless, unlike Chinese, in which the unusual visual appearance of the spaced text format in Chinese may disrupt the habitual reading patterns used by experienced readers, readers of Javanese script have had a lifetime of experience reading texts with interword spaces in Indonesian (i.e., the official language [and school language] of Indonesia). As the dynamic bilingual language system is operated interactively, the reading strategies from the Latin-script of Indonesian would have influenced their reading-aloud performance in Javanese script. As they have extensive experience reading a spaced language, readers of Javanese script have developed greater dependence on spaces between words for eye guidance and lexical identification, which could be transferred to reading Javanese script. These findings suggest that the effectiveness of a visual cue, such as interword spaces to mark word boundaries, may be determined by whether readers are familiar with unspaced texts (Winskel et al., 2012).

Regarding the role of color-based segmentation information, we found a parallel developmental trajectory as reported by previous experiments in Chinese (Pan et al., 2020; Perea & Wang, 2017; Song et al., 2021). We found a facilitative effect of coloring alternating words for developing readers with limited reading experience but not for skilled readers. For developing readers, boundary information via colors provided relevant visual cues to aid word segmentation and reading, probably because they do not have optimal statistical knowledge to segment words and smaller perceptual spans. Notably, with the accumulation of reading experience and vocabulary knowledge, readers would gradually reduce their reliance on low-level word boundary

cues for word segmentation in reading habits, as shown in Experiments 4 and 5. It may also be important to note that coloring adjacent words to demarcate word boundaries would produce a somewhat atypical format for skilled readers, and this format unfamiliarity may counteract the potential benefit of word segmentation (see Zhou et al., 2018).

We acknowledge that, for a more detailed analysis of the word segmentation process in Javanese script, future research should examine the effects of the two visual cues by registering participants' eye movements during sentence reading. Note, however, that the findings reported Perea and Wang (2017) with alternating-color texts on reading aloud in Chinese have been replicated in subsequent eye movement research from various research teams (e.g., Pan et al., 2020; Song et al., 2021; Zhou et al., 2018, 2020). We hope the present findings will serve to further drive research on reading in Javanese script, as the linguistic nuances of this script may offer valuable insights for a universal model of reading.

Pedagogically, our findings are of significance for the instruction of Javanese script. Explicit word boundary marker is an efficient method to facilitate students' reading acquisition in their early years of reading development (Pan et al., 2020; Perea & Wang, 2017). Therefore, when arranging textbooks in Javanese, interword spaces could be introduced to help developing readers visually separate continuous letters into words (e.g., Shen et al., 2012). Indeed, this strategy occurs in the initial moments of learning to read in various writing systems (e.g., Thai, Hiragana). For instance, in Thailand, children in Grade 1 learn spaced sentences, and they only move on to unspaced sentences in Grade 2 (Kasispa et al., 2013). This way, Javanese learners would have more chances to promote their vocabulary capacity and reading accumulation, positively influencing language learning. The application of spacing in teaching an unspaced script like Javanese seems preferable to alternating color, as all readers of Javanese script will be primarily taught in Indonesian, which uses interword spaces. Of course, the practical values of this manipulation of Javanese materials and text instruction remain to be confirmed in large-scale teaching practices.

To sum up, the present experiments showed that the insertion of interword spaces and color alternation across words for developing readers are helpful word segmentation cues in Javanese script. Skilled adult readers also read aloud faster the texts faster with interword spaces than the standard unspaced texts, but color information did not affect reading speed. One reason for the special role of interword spaces in Javanese script could be attributable to the positive transfer from their habit of reading in their first language (Indonesian, which uses interword spaces). From an educational perspective, our findings stress the benefits of a teaching approach and textbook layout that incorporate interword spacing when initially learning Javanese script.

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Author Contributions X.G. and H.H. designed the experiments. H.H. conducted the experiments. X.G. and M.P. analyzed the data and wrote the main manuscript text. All authors reviewed the manuscript.

Data availability The materials, data and analyses are available at the following OSF link: https://osf.io/9x2d6/?view_only=03fcb580d3044ade86835b6213804df8.

Declarations

Competing interests The authors declare they do not have any competing interests that are applicable to the content of this paper.

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