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Disrupting uniformity: Feature contrasts that reduce crowding interfere with peripheral word recognition

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ABSTRACT

Peripheral word recognition is impaired by crowding, the harmful influence of surrounding objects (flankers) on target identification. Crowding is usually weaker when the target and the flankers differ (for example in color). Here, we investigated whether reducing crowding at syllable boundaries improved peripheral word recognition. In Experiment 1, a target letter was flanked by single letters to the left and right and presented at 8° in the lower visual field. Target and flankers were either the same or different in regard to contrast polarity, color, luminance, and combined color/luminance. Crowding was reduced when the target differed from the flankers in contrast polarity, but not in any of the other conditions. Using the same color and luminance values as in Experiment 1, we measured recognition performance (speed and accuracy) for uniform (e.g., all letters black), congruent (e.g., alternating black and white syllables), and incongruent (e.g., alternating black and white non-syllables) words in Experiment 2. Participants verbally reported the target word, briefly displayed at 8° in the lower visual field. Congruent and incongruent words were recognized slower compared to uniform words in the opposite contrast polarity condition, but not in the other conditions. Our results show that the same feature contrast between the target and the flankers that yielded reduced crowding, deteriorated peripheral word recognition when applied to syllables and non-syllabic word parts. We suggest that a potential advantage of reduced crowding at syllable boundaries in word recognition is counteracted by the disruption of word uniformity.

1. Introduction

Crowding is the harmful influence of surrounding objects (flankers) on target identification (Bouma, 1970; He, Cavanagh, & Intriligator, 1996; Pelli, Palomares, & Majaj, 2004; Stuart & Burian, 1962; Strasburger, Harvey, & Rentschler, 1991; Sayim & Wagemans, 2017; Toet & Levi, 1992; for reviews see Herzog, Sayim, Chicherov, & Manassi, 2015; Levi, 2008; Whitney & Levi, 2011). The minimum distance at which flankers no longer interfere with target identification, called the critical spacing, is proportional to the eccentricity of the target. Deleterious target-flanker interactions are often estimated to take place when the flankers are situated within about half the target's eccentricity (Bouma, 1970; also called "Bouma's law"). The spatial extent of crowding (Levi, Hariharan, & Klein, 2002; Toet & Levi, 1992) as well as crowding strength (Loomis, 1978) is more pronounced in peripheral compared to foveal vision, and independent of target size (Tripathy & Cavanagh, 2002).

Crowding affects common tasks such as visual search, face recognition, and reading (Levi, 2008; Whitney & Levi, 2011). Reading and word recognition are prototypical examples for tasks strongly influenced by crowding. When the spacing between letters is smaller than the critical spacing, letters crowd each other, thereby impairing word recognition (Pelli & Tillman, 2008). In this way, strong crowding in the periphery may constitute a major reason for poor peripheral reading (Pelli et al., 2007). In normal readers, peripheral reading performance does not reach the level obtained in the fovea (Latham & Whitaker, 1996), even after compensating for letter size (Chung, Mansfield, & Legge, 1998). Poor peripheral reading performance poses a particular problem when foveal vision is impaired and cannot be used for reading (Legge, Rubin, Pelli, & Schleske, 1985). For example, due to symptomatic central visual field loss, age-related macular degeneration patients rely strongly on peripheral vision, resulting in a major impairment of reading (Fine, Berger, Maguire, & Ho, 2000). Since peripheral reading is impeded by crowding, a reduction of crowding (uncrowding) could be expected to improve peripheral reading.

One way to reduce crowding is to increase the spacing between target and flankers (Bouma, 1970; Chung, Levi, & Legge, 2001). Crowding is also reduced with weak target-flanker grouping (Banks &

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Prinzmetal, 1976; Herzog et al., 2015; Livne & Sagi, 2007, 2010; Manassi, Sayim, & Herzog, 2012, 2013; Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim & Cavanagh, 2013; Sayim, Westheimer, & Herzog, 2008, 2010), and low target-flanker similarity (e.g., Kooi, Toet, Tripathy, & Levi, 1994). For example, when the target and the flankers differ in orientation (Andriessen & Bouma, 1976), contrast polarity (Chung & Mansfield, 2009; Kooi et al., 1994; Sayim, Westheimer, & Herzog, 2008), shape (Kooi et al., 1994), binocular disparity (Kooi et al., 1994; Sayim et al., 2008), letter complexity (Bernard & Chung, 2011), or color (Kooi et al., 1994; Manassi, Sayim, & Herzog, 2012; Põder, 2007; Sayim et al., 2008), crowding is usually weaker compared to when the target and the flankers are the same on these dimensions.

As letter identification improves when increasing the spacing between target and flankers (Bouma, 1970; Chung et al., 2001), a similar benefit might be expected in word recognition. In particular, increasing the spacing between letters, and thereby reducing crowding between them, could be assumed to result in improved word recognition and reading. However, reading speed did not improve with increased compared to standard letter spacing (Chung, 2002). One reason for the absence of improvement could be that the increased letter spacing decreased the visual span, i.e., the number of letters recognized without eye movements (Yu, Cheung, Legge, & Chung, 2007). Since a smaller visual span is associated with slower reading (Legge et al., 2007), it might counteract a possible advantage of reduced crowding between letters. Importantly, large letter spacings may also come with the cost of disrupting the word form (Chung, 2002). Such a disruption of word form potentially neutralizes any beneficial effect of reduced letter crowding, which also might explain the lack of improved reading performance for letter spacings above the standard spacing (Chung, 2002; Legge et al., 1985).

As noted above, crowding can be reduced by making the target and the flankers more distinct, for example, by using flankers of opposite contrast polarity than the target (e.g., a black target with white flankers; Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Sayim et al., 2008; Rosen & Pelli, 2015). However, alternating the contrast polarity of neighboring letters did not improve peripheral reading performance compared to same polarity letters (Chung & Mansfield, 2009). Possibly, alternating the contrast polarity of neighboring letters was not beneficial because local uncrowding of individual letters was counteracted by the grouping of all letters into a single 'alternating pattern' (Sayim et al., 2008; Manassi et al., 2012; Rosen & Pelli, 2015). Moreover, when asked to report all instead of only the central letter of a peripherally presented trigram, the advantage for the recognition of the central letter flanked by opposite compared to same contrast polarity letters was greatly reduced (Chung & Mansfield, 2009) or abolished (Rummens & Sayim, 2019). Overall, these results suggest that reducing crowding between neighboring letters is ineffective for increasing peripheral reading performance.

Beyond letters, syllables are proposed as functional units in visual word recognition (Ferrand & Segui, 2003; Stenneken, Conrad, & Jacobs, 2007). For example, in contrast to beginning readers who are assumed to serially process letters in order to recognize words, more advanced readers might be able to process letters in parallel, enabling the holistic processing of letter chunks, such as syllables (Ehri & McCormick, 1998; Grainger & Ziegler, 2011). Different characteristics of syllables have been investigated in the context of syllabic word processing. When primed with the initial syllable, participants named a subsequent target word faster (Ferrand, Segui, & Grainger, 1996) and showed shorter lexical decision times than when primed with the first syllable plus/minus one letter (Carreiras & Perea, 2002). Also the number of syllables within a word is informative for whether syllable-based word processing occurs. For example, performance in a lexical decision and a word naming task was inferior for three-syllable words compared to two-syllable words of equal length, providing support for analytic processing by syllables (at least for the investigated low-frequency French words; Ferrand & New, 2003). Further evidence for syllabic processing comes from studies showing faster word naming (Perea & Carreiras, 1998) and slower lexical decisions (Conrad & Jacobs, 2004; Mathey & Zagar, 2002; Perea & Carreiras, 1998) when the initial syllables were of relatively high frequency. Overall, this suggests that syllables are important processing units in visual word recognition, and peripheral reading performance may benefit from reduced crowding between syllables.

A potential advantage of reduced crowding at syllable boundaries for peripheral word recognition was suggested by the findings of Bernard, Calabrèse, and Castet (2014). Their results revealed that peripheral recognition was faster for words consisting of alternating red and black syllables (color/syllable congruent) compared to entirely black words (uniform). No difference in reading speed was found between uniform words (e.g., all letters black) and color/syllable incongruent words (i.e., words consisting of black and red non-syllabic word parts). The authors argued that the facilitating effect in the congruent condition was due to improved syllable decomposition and observers' strategies, but not due to reduced crowding (because of no improvement in the incongruent condition). Since crowding was not measured directly, it is unclear whether the suggested improved word segmentation coincided with reduced crowding at the color boundaries. Hence, it is possible that there is a dissociation between feature contrasts required for improving syllable segmentation, and for reducing crowding.

While improved syllable segmentation of words can facilitate peripheral word recognition (Bernard et al., 2014), there might also be a cost when syllables' features alternate. In particular, disrupting uniformity of words might hinder word recognition. For example, when alternating lower and higher letter cases within a word, identification was worse compared to words with letters of the same case (Coltheart & Freeman, 1974; Mayall & Humphreys, 1996). Similarly, strings of letters with the same font were recognized faster compared to strings of letters with different fonts (Sanocki, 1987,1988). Hence, fonts with highly distinctive letters may negatively impact letter and word recognition (Sanocki & Dyson, 2012). However, words in Eido, a font with reduced letter similarity, were recognized faster than in standard fonts (e.g., Courier; Bernard, Aguilar, & Castet, 2016). The beneficial effect of Eido-letters may reflect an optimal balance of letter distinctiveness and letter uniformity (Sanocki & Dyson, 2012), reducing crowding between letters while preserving sufficient uniformity within a word. Taken together, dissimilarity between a word's constituting parts might on the one hand hinder word recognition by disrupting uniformity, and on the other hand facilitate word recognition by improving segmentation and (potentially) reducing crowding.

Here, we investigated if feature contrasts that reduce crowding between letters modulated peripheral word recognition when applied to syllable boundaries. First, in a standard crowding paradigm, we investigated to what extent differences in contrast polarity, color, luminance, and combined color/luminance yielded uncrowding compared to conditions in which they were the same. Next, we tested whether identical feature contrasts modulated word recognition when applied to syllables and non-syllabic word parts compared to uniform words. Since feature contrasts between syllables on the one hand might result in improved syllable segmentation, and on the other might come with the drawback of disrupting word uniformity, the conditions under which different feature contrasts positively or negatively affect word recognition are unclear.

Participants performed a letter identification task in Experiment 1, verbally reporting the central letter of a peripherally presented three letter string (trigram). There were two conditions. In the Uniform condition, all letters of the trigram had the same color and luminance. In the Alternating condition, the target letter differed in color and/or luminance from its flanking letters. In Experiment 2, we measured peripheral word recognition performance (speed and accuracy). Different word parts (syllables or non-syllabic parts of words) were either the same or varied in color, luminance, or both. In the Uniform condition, all letters of the words were of the same color and luminance (e.g., all letters red). There were two Alternating conditions (Congruent and Incongruent), in which adjacent word parts were of different color and/or luminance. In the Congruent condition, neighboring syllables had different colors and/or luminance to reduce crowding at syllable boundaries (e.g., alternating black and white syllables). In the Incongruent condition, adjacent non-syllabic word parts were of different color and/or luminance (e.g., alternating black and white non-syllables). If these feature contrasts between syllables improved peripheral word recognition, the Congruent condition but not the Incongruent condition would be expected to yield an advantage compared to the Uniform condition. There were four different color/luminance conditions, including one identical to Bernard et al. (2014) where alternating red and black syllables of different luminance improved performance. The other color/luminance conditions allowed us to investigate the roles of color and luminance separately.

Experiment 1 revealed reduced crowding (i.e., smaller critical spacing) in the Alternating compared to the Uniform condition when the target and the flankers were of opposite contrast polarity. The other color and/or luminance contrasts between the target and the flanking letters failed to uncrowd the target letter. In Experiment 2, the facilitating effect of syllable segmentation found by Bernard et al. (2014) was not replicated. Recognition performance did not improve for words with alternating red and black syllables compared to uniform words. Also, the other color and luminance conditions did not show improved recognition performance in the Congruent compared to Uniform conditions. To the contrary, Experiment 2 revealed slower recognition performance for words in which parts alternated in opposite contrast polarity (Congruent and Incongruent) compared to words consisting of same contrast polarity (Uniform). Hence, the only manipulation (opposite contrast polarity) that weakened crowding in Experiment 1 interfered with word recognition in Experiment 2. We attribute the deterioration of performance in Experiment 2 to a disruption of word uniformity, and suggest that feature contrasts that reduce crowding interfere with peripheral word recognition.

2. Experiment 1: peripheral letter recognition

2.1. Material and methods

2.1.1. Subjects

Twelve subjects (F = 9, M = 3) within an age range from 21 to 35 years participated in exchange for course credits or monetary compensation. All participants reported normal or corrected-to-normal vision. None of the subjects were color deficient, which was validated by the administration of the Ishihara test (Clark, 1924). Written informed consent was obtained from all participants. Experiments complied with the ethical standards of the Declaration of Helsinki and were approved by the Ethics Committee of the University of Bern.

2.1.2. Apparatus

Stimuli were displayed on a 22 in. CRT monitor (P1230, HP, refresh rate = 110 Hz, resolution = 1152 × 864) by running a custom-written PsychoPy (Peirce, 2007) program on a PC computer. Using a head and chin rest, participants viewed the screen binocularly from a distance of 57 cm. The experimental room was dimly lit.

2.1.3. Stimuli

The stimuli were letter trigrams consisting of three randomly selected unique lowercase letters from the 26 letters of the alphabet. The central letter of the trigram was the target, with a flanking letter presented both on the left and right. We used five different target-flanker distances to measure the critical spacing; spacings were defined in terms of lowercase x-height (0.8x, 1x, 1.25x, 1.6x, and 2x). The height of a lowercase x corresponded to 1°.

There were four color/luminance conditions: Combined, Achromatic, Isoluminant, and Opposite Contrast Polarity (see Table 1). In the Combined condition, trigrams were black and/or red with different luminance (black: 0.03; red: 20.2 cd/m^2; as in Bernard et al., 2014). In the Achromatic condition, the same luminance values as in the Combined condition were used without color differences (black: 0.03; grey: 20.2 cd/m^2). In the Isoluminant condition, trigrams were grey and/or red of identical luminance (20.2 cd/m^2). In these three conditions (Combined, Achromatic, and Isoluminant) trigrams were presented on a white background (79.1 cd/m^2). In the Opposite Contrast Polarity condition, trigrams were white (79.1 cd/m^2) and/or black (0.03 cd/m^2), presented on a middle grey (39.6 cd/m^2) background.

Trigrams were either Uniform or Alternating. In the Uniform condition, all letters of the trigram had the same color and luminance. All Uniform trigrams were counterbalanced in color/luminance ("trigram pattern subtypes"). For example, the same number of trigrams in the Combined condition consisted of all black and all red letters (see Table 1). In the Alternating condition, the central letter differed in color and/or luminance from its flanking letters. All Alternating conditions were counterbalanced in regard to the order of color/luminance within a trigram. For example, in the Combined condition, half of the Alternating trigrams had a red target letter, while the other half had a black target letter (see Table 1).

2.1.4. Procedure

Experiment 1 measured identification accuracy of the central (target) letter of the peripherally presented trigram. Fig. 1 provides an overview of the experimental procedure. Throughout the experiment, subjects fixated the centrally presented red fixation dot (radius = 0.3°). Upon pressing the spacebar, a trigram was briefly (150 ms) displayed at 8° eccentricity in the lower visual field. Targets were shown centered on the vertical midline with flankers to the left and right. Participants verbally reported the central letter. The experimenter provided feedback on the accuracy after each trial. Trials in which participants reported to have looked at the trigram directly were excluded from the analyses (less than one percent of the trials).

Experiment 1 included three within-subject variables: color/luminance, trigram pattern, and spacing. The participants' performance was measured as a function of target-flanker spacing.

There were two sessions (on two different days). In each session, two of the four color/luminance conditions (Combined, Achromatic, Isoluminant, Opposite Contrast Polarity) were completed. Each color/luminance condition was completed before the next one. The order of the color/luminance conditions was randomized, and blocked by trigram pattern subtype. For example, in the Achromatic condition, all trials of the Uniform grey trigrams at the five spacings would be completed before proceeding to either the Uniform black trigrams, or the Alternating trigrams with, e.g., the red target letter. Trigram pattern subtype and letter spacing blocks were both completed in a randomized order. For each color/luminance condition, participants completed 40 trials per trigram pattern (20 for each subtype) at each of the five spacings. As a baseline, in each color/luminance condition, 40 trials of unflanked letters (20 trials of each color/luminance) were measured. Overall, this resulted in 440 trials per color/luminance condition (880 trials per session, and 1760 trials for the entire experiment).

2.2. Results

Per color/luminance by trigram pattern combination, we estimated the letter spacing at which participants reached 50% correct (threshold) by fitting a cumulative Gaussian function to the individual data (psignifit 4 toolbox for Matlab; The MathWorks, MA). Next, separately for each color/luminance condition, we conducted a repeated measures ANOVA to compare the thresholds between the Alternating and the Uniform conditions.

In the Opposite Contrast Polarity condition, the threshold was lower in the Alternating compared to the Uniform condition ($F(1,11) = 10.90$, $p < 0.01$; see Fig. 2D). In the Combined (F

Table 1
Overview of the color/luminance by trigram pattern conditions. Trigram pattern subtypes are separated by a dashed line.

		COLOR / LUMINANCE			
		COMBINED	ACHROMATIC	ISOLUMINANT	OPPOSITE CONTRAST POLARITY
TRIGRAM PATTERN	ALTERNATING	xyz	xyz	xyz	xyz
		xyz	xyz	xyz	xyz
	UNIFORM	xyz	xyz	xyz	xyz
		xyz	xyz	xyz	xyz
LUMINANCE (cd/m^2)	white	79.1	79.1	79.1	79.1
	black	.03	.03	–	.03
	grey	–	20.2	20.2	39.6
	red	20.2	–	20.2	–

(1,11) = 0.41, p = .54), Achromatic (F(1.11) = 0.97, p = 0.35), and Isoluminant (F(1,11) = 3.69, p = 0.08) condition, there was no difference between the Alternating and Uniform conditions (see Fig. 2A–C). When including color/luminance as a factor, there was a main effect of trigram pattern (F(1,11) = 7.04, p = .02) and an interaction between color/luminance and trigram pattern (F(3,33) = 4.15, p = .01). Tukey tests confirmed that the Alternating and Uniform trigrams differed only in the Opposite Contrast Polarity condition ($p < .01$).

Separately for each color/luminance condition, we compared the recognition performance for the unflanked letters (e.g., single black versus single red letters in the Combined condition). There were no differences in any of the color/luminance conditions (Combined: F (1,11) = 0.06, p = .81; Achromatic: F(1,11) = 0.45, p = .52; Isoluminant: F(1,11) = 0.11, p = .74; Opposite Contrast Polarity: F (1,11) = 0.43, p = .53). Performance for single letters was above 95 percent correct for each color/luminance.

2.3. Discussion

The results of Experiment 1 showed a smaller critical spacing of crowding for the Alternating compared to the Uniform trigrams in the Opposite Contrast Polarity condition. No difference was found between Alternating and Uniform trigrams in the Combined, Achromatic, and Isoluminant conditions. Our results confirmed the strong uncrowding effect of opposite contrast polarity (e.g., Chung & Mansfield, 2009; Kooi et al., 1994). The absence of uncrowding effects in the other conditions could be due to insufficient feature contrast between the color/luminance values. However, although most studies use strong color contrasts (e.g., red and green) to obtain uncrowding (e.g., Kooi et al., 1994; Manassi et al., 2012; Sayim et al., 2008), uncrowding was also shown in conditions similar to ours (black and red; Põder, 2007). In the Combined condition, the color and luminance manipulation was (nearly) identical to the manipulation in the study by Bernard et al. (2014). Since we did not observe any uncrowding effect in this condition, one might speculate that crowding at the color boundaries was not reduced in their study either.

3. Experiment 2: peripheral word recognition

Experiment 1 showed uncrowding only when the target and the

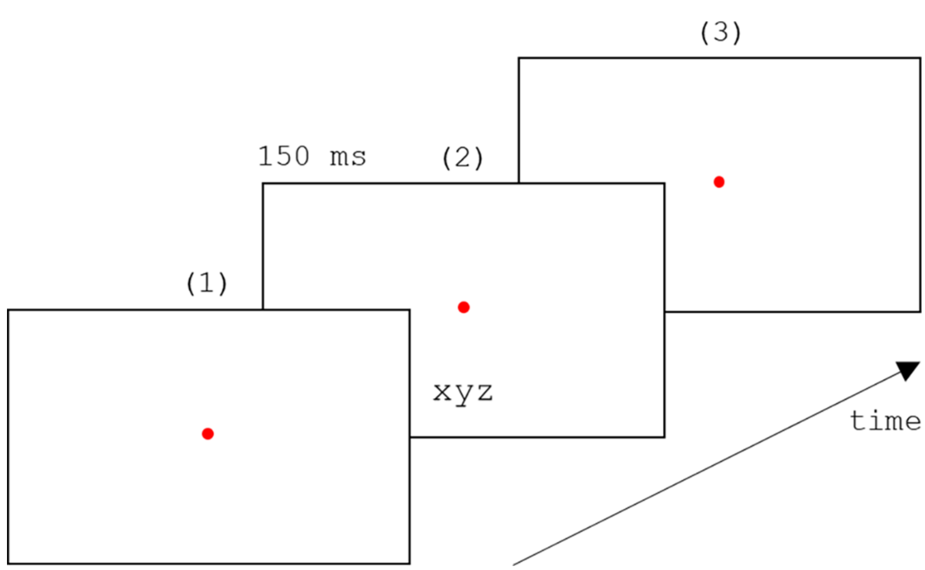

Fig. 1. Procedure of Experiment 1. (1) Participants fixated a centrally presented fixation dot. (2) Stimulus presentation was initiated by a key press. The trigram was presented for 150 ms at 8° eccentricity in the lower visual field. (3) After stimulus presentation, participants verbally reported the central target letter.

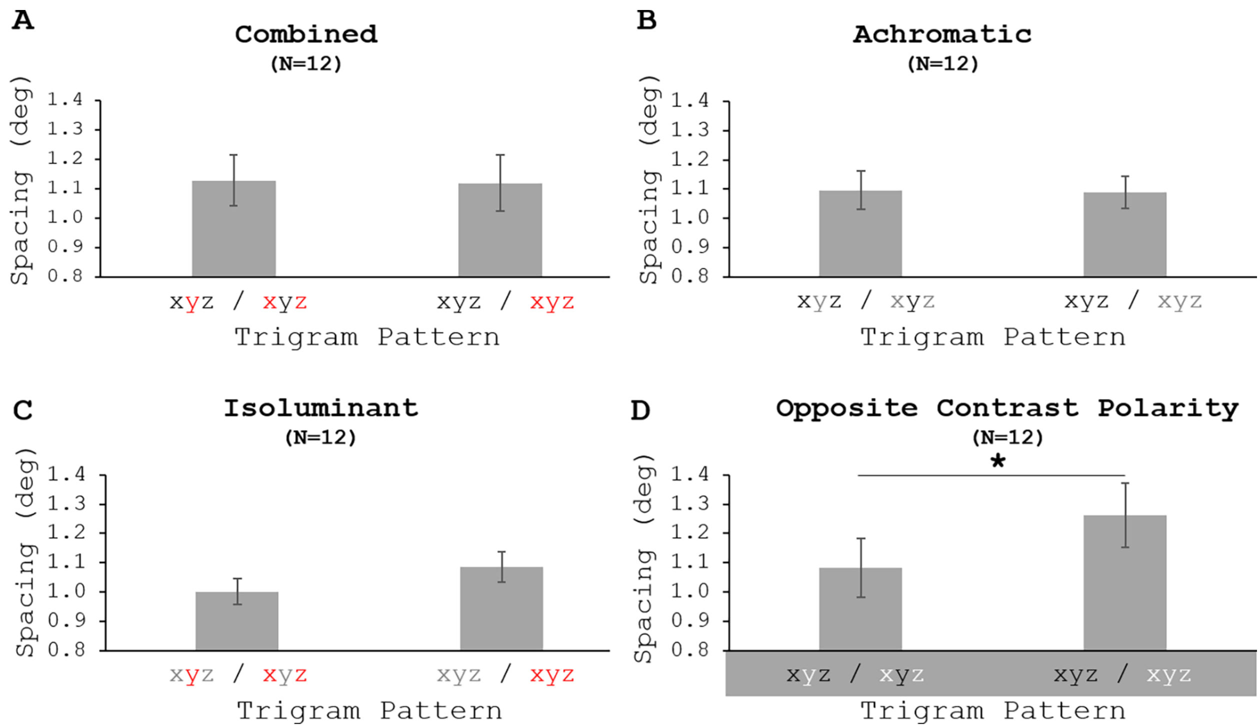

Fig. 2. Results of Experiment 1. No differences in critical spacing were found for Alternating and Uniform trigram patterns in the Combined (A), Achromatic (B), and Isoluminant (C) condition. In the Opposite Contrast Polarity (D) condition, the threshold was lower for Alternating compared to Uniform trigrams. The asterisk indicates a significant difference at the 0.05 alpha level. Error bars represent the mean +/-1 standard error.

flankers differed in contrast polarity but not in any of the other conditions. In Experiment 2, we used the same color/luminance conditions as in Experiment 1, to investigate if peripheral word recognition improved or deteriorated when word parts were of the same or different color/luminance. In particular, we tested whether there was a benefit for recognition performance for words with syllables alternating in color/luminance (Congruent) compared to words without this alternation (Incongruent and Uniform). If the same feature contrasts that reduced letter crowding in Experiment 1 improved word recognition when applied to syllables, we would expect superior recognition for Congruent but not for Incongruent words compared to Uniform words in the Opposite Contrast Polarity condition only (based on the results of Experiment 1). On the other hand, feature contrasts (here, differences in color and/or luminance) between word parts can disrupt word uniformity, and thereby potentially harm word recognition. A possible advantage of reduced crowding between syllables to facilitate word recognition, might be hindered by the disadvantage of disrupted uniformity.

3.1. Material and methods

3.1.1. Subjects

The same twelve subjects that participated in Experiment 1 completed Experiment 2. They were native German speakers and self-reported non-dyslexics.

3.1.2. Apparatus

The apparatus was identical to Experiment 1, with the exception that eye movements of the dominant eye were monitored with an eye-tracker (EyeLink 1000 Tower Mount, SR Research, Mississauga, Ontario, Canada) at a refresh rate of 1000 Hz.

3.1.3. Stimuli

Stimuli were randomly drawn from a set of 4000 two- and three-syllable German words (2000 words each). The 1400 most frequent two- and three-syllable words were used for the experimental trials, resulting in 2800 experimental stimuli. The remaining 1200 words in our stimulus set were practice stimuli. The words were selected from the SUBTLEX-DE database (Brysbaert et al., 2011). Offensive words were not included. For the division of the words into syllables, we used the Python hyphenation tool Pyphen (http://pyphen.org). Additionally, a native German speaker verified the words' hyphenation and spelling.

Words were displayed in the mono-spaced Courier New font. The letter size was defined so that the height of a lowercase x subtended 1° on the screen. Center-to-center letter spacing was 1.4°. Words were presented at 8° eccentricity (center-to-center distance between the fixation dot and a lowercase x letter), centered on the vertical midline in the lower visual field. Each word was presented only once to each participant.

There were four color/luminance conditions identical to Experiment 1: Combined, Achromatic, Isoluminant, and Opposite Contrast Polarity. We used three different word segmentation conditions: Congruent, Incongruent, and Uniform. The Congruent and Incongruent condition were both "Alternating" conditions, consisting of words with parts alternating in color/luminance. In the Congruent condition, the alternation of color and/or luminance coincided with syllable boundaries. In the Incongruent condition the alternation of color and/or luminance did not coincide with syllable boundaries, but was randomly shifted one character to the left or right from the syllable boundaries. All Alternating conditions were counterbalanced in regard to the order of color/luminance within a word ("word segmentation subtypes"; for example, in the Achromatic condition, half of the words started with black, the other half with grey letters, see Table 2). Additionally, we included an Incongruent condition in which all consonants were of one, and vowels of the other color/luminance. In the Uniform condition, the whole word was shown in the same color and luminance (for example, in the Achromatic condition, half the words were black and the other half grey).

Table 2
Overview of the color/luminance by word segmentation conditions for an exemplary three-syllable word. Colors and luminance values are identical to those in Experiment 1. Word segmentation subtypes are separated by a dashed line.

			COLOR / LUMINANCE			
			COMBINED	ACHROMATIC	ISOLUMINANT	OPPOSITE CONTRAST POLARITY
WORD SEGMENTATION	ALTERNATING	CONGRUENT	zusammen	zusammen	zusammen	zusammen
			zusammen	zusammen	zusammen	zusammen
		INCONGRUENT	zusammen	zusammen	zusammen	zusammen
			zusammen	zusammen	zusammen	zusammen
			zusammen	zusammen	zusammen	zusammen
	UNIFORM		zusammen	zusammen	zusammen	zusammen
			zusammen	zusammen	zusammen	zusammen

3.1.4. Procedure

In Experiment 2, we used a peripheral word recognition task. There were two independent variables with four color/luminance conditions and three word segmentation conditions (see Table 2).

Participants initiated each trial by pressing the spacebar, resulting in the presentation of the red fixation dot in the center of the screen. After fixation of the dot for 800 ms, a word was shown for a maximum duration of 3 s. As soon as participants recognized the word, they pressed the spacebar, which made the word disappear from the screen. Subsequently, participants reported the word out loud, after which they received verbal feedback from the experimenter on the accuracy of the provided answer (correct/incorrect). After 3 s without pressing the response key, the word disappeared (time-out trial). Trials in which participants responded within 3 s and time-out trials were both designated as valid. If participants did not keep fixation within an area of 1.2° radius around the fixation dot, the word immediately disappeared and the trial was terminated. These trials were categorized as non-valid, and excluded from the analyses. Fig. 3 shows an overview of the experimental procedure. As dependent variables, reaction time (the time between word stimulus onset and pressing the spacebar) and accuracy were registered.

Participants completed four sessions (one session per day), with each session corresponding to a specific condition of color/luminance. The order of the color/luminance conditions was randomized per participant. Each session started with a practice part, followed by an experimental part. Both the practice and experimental part were preceded by a calibration of the eye tracker. Recalibrations were performed during the experiment when necessary. In the practice part, subjects completed six blocks of the different word segmentation condition subtypes in randomized order. Eight (four) valid trials per word segmentation (subtype) condition were performed. In the experimental part, two times six blocks of the different word segmentation condition subtypes were completed. The order of the six blocks was randomized in the first half, and reversed in the second half. Per color/luminance by word segmentation condition, subjects were required to complete 80 valid trials (with 40 valid trials for each word segmentation subtype). This resulted in a total of 240 valid experimental trials per session, and 960 valid trials for the whole experiment.

3.2. Results

3.2.1. Reaction time

First, we analyzed reaction times. Trials during which participants did not keep fixation and trials that timed out were not included in the analysis. Within each color/luminance condition, outliers (2 standard deviations below and above the mean) were removed on individual and sample level. Only trials with correctly identified words were retained. Separately for each condition of color/luminance, we compared the reaction times between the different word segmentation conditions (see Fig. 4).

Separately for each color/luminance condition, a one-way repeated measures ANOVA was conducted with reaction time as dependent variable and word segmentation as within-subject factor. There was no difference in reaction times between Congruent, Incongruent, and Uniform words in the Combined ($F(2,22) = 1.79$, $p = .19$), Achromatic ($F(2,22) = 0.21$, $p = .81$), and Isoluminant ($F(2,22) = 1.34$, $p = .28$)

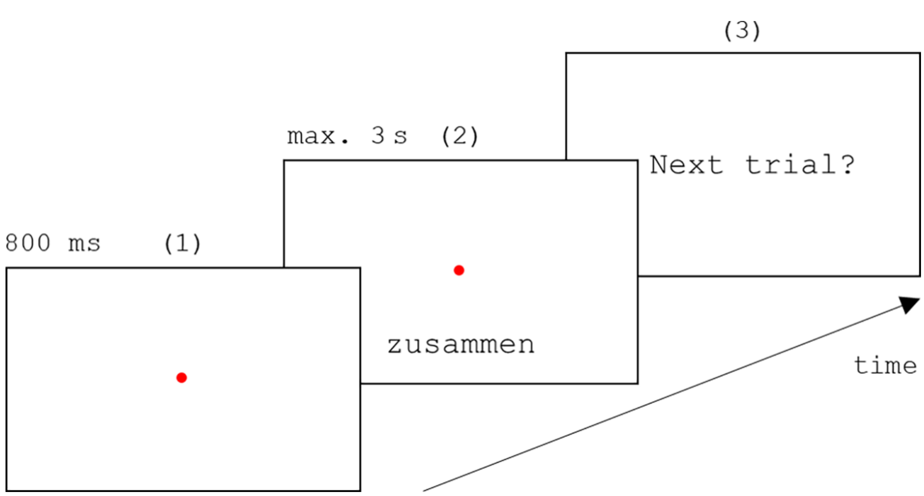

Fig. 3. The experimental procedure of Experiment 2. (1) Participants fixated the fixation dot for 800 ms. (2) Next, a word was presented at 8° eccentricity in the lower visual field for a maximum duration of 3 s. When a participant recognized a word within the 3 s timeframe, he/she pressed the response key and said the word out loud. (3) Pressing the response key resulted in the immediate removal of the stimulus from the screen, asking the participant to continue to the next trial (in German).

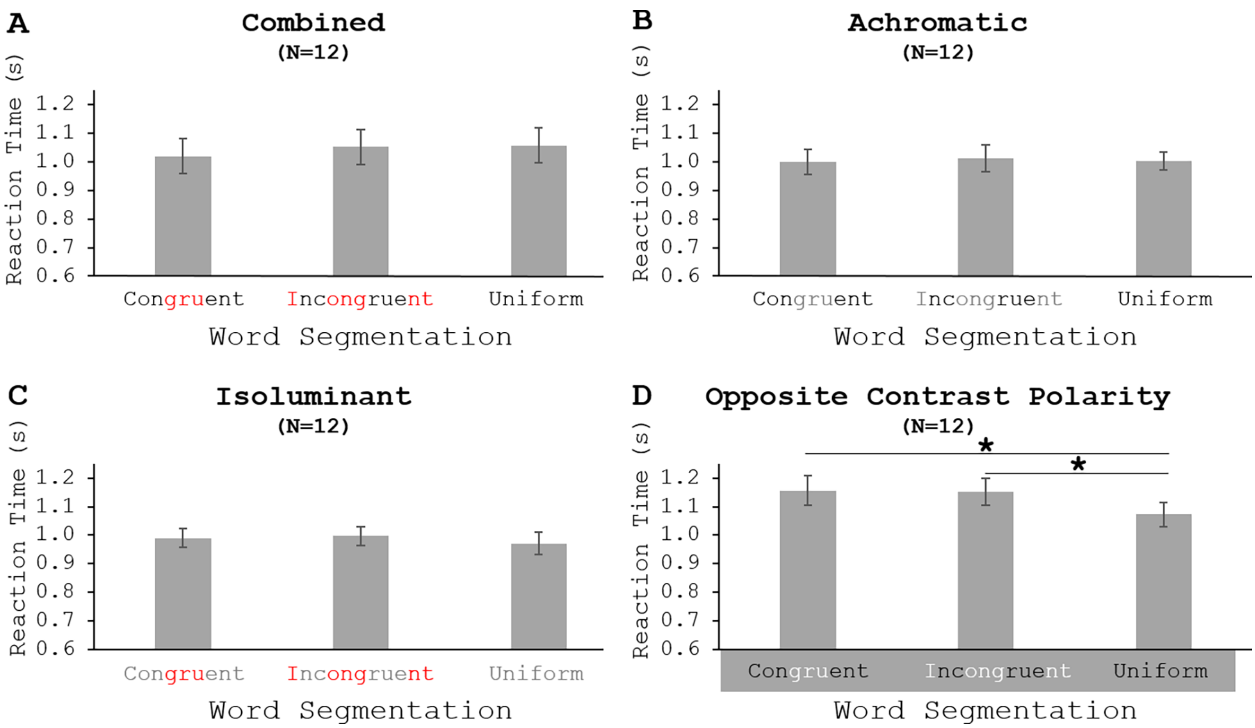

Fig. 4. Comparisons of reaction times in seconds between the different word segmentation conditions, separately for each color/luminance condition. No differences in reaction time were found between the word segmentation conditions in the Combined (A), Achromatic (B), and Isoluminant (C) condition. In the Opposite Contrast Polarity (D) condition, reaction times were slower for Congruent and Incongruent words compared to Uniform words. Asterisks indicate a significant difference at the 0.05 alpha level. Error bars represent the mean ± 1 standard error.

conditions (see Fig. 4A-C). In the Opposite Contrast Polarity condition, there was a main effect of word segmentation ($F(2,22) = 11.40$, $p < .001$). Subsequent post-hoc Tukey tests revealed that reaction times were significantly faster in the Uniform condition compared to both the Congruent ($p < .001$) and the Incongruent ($p = .002$) condition (see Fig. 4D). When adding color/luminance as a factor, there were main effects of both color/luminance ($F(3,33) = 5.94$, $p < .01$) and word segmentation ($F(2,22) = 7.10$, $p < .01$), and an interaction between color/luminance and word segmentation ($F(6,66) = 3.44$, $p < .01$). The interaction was mainly driven by slower reaction times for Congruent and Incongruent compared to Uniform words in the Opposite Contrast Polarity condition ($p < .01$ for both comparisons).

Next, we tested if there was an effect of the number of syllables on reaction time. To this end, separately for each color/luminance condition, we conducted a two-way repeated measures ANOVA, adding a two-level syllable factor (2 and 3 syllables) to the initial model. In all four color/luminance conditions, we found a main effect of syllable number (Combined: $F(1,11) = 103.35$, $p < .001$; Achromatic: $F(1,11) = 89.38$, $p < .001$; Isoluminant: $F(1,11) = 64.42$, $p < .001$; Opposite Contrast Polarity: $F(1,11) = 20.14$, $p < .001$), showing faster reaction times for two-syllable when compared to three-syllable words. None of the interactions between word segmentation and number of syllables reached significance (Combined: $F(2,22) = 0.15$, $p = .86$; Achromatic: $F(2,22) = 0.053$, $p = .95$; Isoluminant: $F(2,22) = 0.38$, $p = .69$; Opposite Contrast Polarity: $F(2,22) = 0.97$, $p = .40$).

Finally, separately for each color/luminance condition, we explored whether there were differences in reaction time between the word segmentation subtypes (shifted boundary versus consonant/vowels) of the Incongruent condition. In none of the color/luminance conditions the comparisons revealed a difference.

3.2.2. Accuracy

For the accuracy analysis, the time-out trials were retained and recoded as incorrect. Separately for each color/luminance condition, we compared accuracies (arcsine transformed proportions correct) between the different word segmentation conditions with a repeated measures ANOVA. In all color/luminance conditions, there was no difference in accuracy between word segmentation conditions (Combined: $F(2,22) = 0.34$, $p = .72$; Achromatic: $F(2,22) = 0.19$, $p = .83$; Isoluminant: $F(2,22) = 0.28$, $p = .76$; Opposite Contrast Polarity: $F(2,22) = 1.01$, $p = .38$) (see Fig. 5). When including color/luminance as a factor, there was a main effect of color/luminance ($F(3,33) = 6.59$, $p < .01$), with worse performance in the Opposite Contrast Polarity condition compared to all three other color/luminance conditions ($p < .05$ for all three comparisons).

Next, we analyzed the effect of the number of syllables on accuracy, for each color/luminance condition, a two-way repeated measures ANOVA revealed a higher proportion correct for the two-syllable compared to the three-syllable words (Combined: $F(1,11) = 65.29$, $p < .001$; Achromatic: $F(1,11) = 54.66$, $p < .001$; Isoluminant: $F(1,11) = 44.75$, $p < .001$; Opposite Contrast Polarity: $F(1,11) = 67.00$, $p < .001$). None of the word segmentation by number of syllables interactions were significant (Combined: $F(2,22) = 0.85$, $p = .44$; Achromatic: $F(2,22) = 0.69$, $p = .51$; Isoluminant: $F(2,22) = 0.35$, $p = .71$; Opposite Contrast Polarity: $F(2,22) = 0.49$, $p = .62$). Finally, separately for each color/luminance condition, we compared accuracies between the word segmentation subtypes of the Incongruent condition. There was no difference in any of the color/luminance conditions.

3.3. Discussion

In the Opposite Contrast Polarity condition, we found that reaction times were faster in the Uniform compared to both Alternating conditions. In the Combined, Achromatic, and Isoluminant conditions, there was no difference in reaction time between the word segmentation conditions. Within each color/luminance condition, no difference in accuracy was found between word segmentation conditions. In all

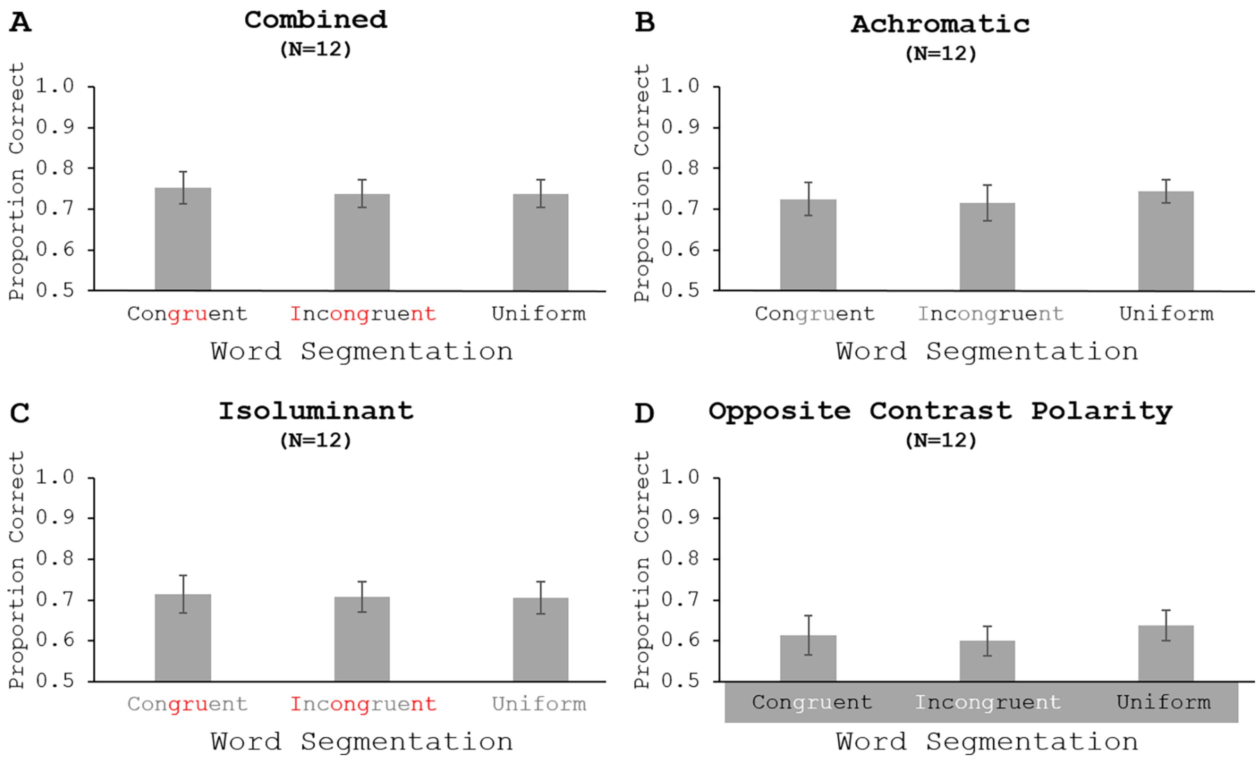

Fig. 5. Comparisons of accuracy between the different word segmentation conditions, separately for each color/luminance condition. In all color/luminance conditions (A–D), there was no difference in accuracy between word segmentation conditions. Error bars represent the mean ± 1 standard error.

color/luminance conditions, two-syllable words were recognized faster and more accurately than three-syllable words.

If peripheral word recognition benefited from color/luminance-induced syllable segmentation, faster reaction times and/or enhanced accuracy in the Congruent but not the Incongruent compared to the Uniform condition would be expected. However, a facilitating effect of syllable segmentation was absent in all color/luminance conditions. To the contrary, our results showed slower recognition in both the Congruent and Incongruent condition compared to the Uniform condition when the alternating word parts were of different polarity (Opposite Contrast Polarity condition). Interestingly, this is the same color/luminance condition that showed reduced crowding in Experiment 1. Hence, the same feature contrast that reduced the critical spacing in the crowding paradigm in Experiment 1, deteriorated word recognition performance in Experiment 2.

Possibly, similar (perceptual) differences are required for the separation of a target from its flankers to yield reduced crowding, as are required for the disruption of word uniformity that interferes with peripheral word recognition.

4. General discussion

In Experiment 1, we investigated the extent to which color and luminance differences between the target and the flankers yielded uncrowding in a letter identification task. In the Opposite Contrast Polarity condition, better performance was found for Alternating compared to Uniform trigrams. This is a standard (un)crowding effect shown in several previous studies (e.g., Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Manassi et al., 2012; Sayim et al., 2008). In the other color/luminance conditions, no advantage was observed for the Alternating compared to the Uniform trigrams.

The results of Experiment 1 can be explained by the similarity of the target and the flankers (e.g., Kooi et al., 1994). In the Uniform conditions, the target and the flankers had the same color and luminance, and the extent of crowding was expected to be large. In the Alternating conditions, however, the extent of crowding was expected to be smaller than in the corresponding Uniform conditions. This effect was only found when the target differed from the flankers in contrast polarity but not in the other color/luminance conditions. As target- flanker similarity differed between the four color/luminance conditions, differences in their capacity to reduce crowding were expected. The absence of differences between the Uniform and Alternating trigrams in the Achromatic, Combined, and Isoluminant conditions suggests that the level of dissimilarity necessary to obtain uncrowding effects was not reached in these conditions. For example, the (color and luminance) differences between black and red targets and flankers in the Combined condition were not sufficient to reduce crowding compared to the corresponding Uniform conditions. In previous research, color differences did not consistently reduce crowding between target and flankers. For example, uncrowding by color only occurred for some but not all observers (Kooi et al., 1994). Moreover, the color contrast between red and black was smaller than the color contrast in other studies that showed uncrowding (red and green targets and flankers; Kooi et al., 1994; Manassi et al., 2012; Sayim et al., 2008). However, uncrowding with red and black targets and flankers has previously been shown in a letter identification task (Põder, 2007), and in the achromatic domain with small contrast differences between the target and the flankers (Chung et al., 2001). Given the absence of a difference in the Combined condition (black and red), it is not surprising that neither the Achromatic condition (with the same luminance values as black and red in the Combined condition) nor the Isoluminant condition (with red and grey of the same luminance) showed any difference between Alternating and Uniform trigrams, as they only differed on a single dimension (either color or luminance) from each other, compared to both color and luminance in the Combined condition.

An alternative explanation for the absence of uncrowding in the Combined, Isoluminant, and Achromatic conditions is high performance with Uniform trigrams, making an additional improvement with Alternating trigrams unlikely. However, although there seems to be a modest trend for better performance in the Uniform Combined, Isoluminant, and Achromatic conditions compared to the Uniform Opposite Contrast Polarity condition where we did find an improvement with Alternating compared to Uniform trigrams, pairwise comparisons between Uniform trigrams of each color/luminance did not reveal any differences. While we did not test if perceptual similarity differed between the conditions, for example, if the white letters differed more strongly from black letters (on the grey background) than the red from the black letters (on the white background), the crowding results themselves are an indirect measure of the similarity between the letters of different color/luminance: Uncrowding is only expected when the target and the flankers are (perceptually) sufficiently different.

In Experiment 2, we investigated if the same color and luminance differences as in Experiment 1 improved or deteriorated peripheral word recognition (reaction time and accuracy) when applied to neighboring syllables and non-syllabic word parts compared to conditions with Uniform words. Performance was slower when the words consisted of Alternating contrast polarity parts, in both the Congruent and Incongruent condition, compared to words of Uniform contrast polarity. Word recognition in the other Alternating color/luminance conditions was not different than in their Uniform counterparts. Hence, the only color/luminance condition in which alternating word parts interfered with word recognition in Experiment 2 was the same that yielded uncrowding in Experiment 1.

However, in contrast to Experiment 1, there was no improvement in the Alternating Contrast Polarity Condition compared to the Uniform condition, but a deterioration. There are several differences between Experiments 1 and 2 that might explain the opposing effects of facilitation (Experiment 1) and deterioration (Experiment 2). First, whereas the stimuli in Experiment 1 consisted of only three letters, they consisted of multi-syllable words in Experiment 2. More items are usually expected to yield stronger crowding (Pelli et al., 2004; Wilkinson, Wilson, & Ellemberg, 1997), at least when there is strong grouping between the target and the flankers (Banks & Prinzmetal, 1976; Banks & White, 1984; Manassi et al., 2012; Sayim et al., 2008). Similarly, stimuli in Experiment 2 are higher in complexity which has been shown to be an important factor in crowding (Bernard & Chung, 2011; Zhang, Zhang, Xue, Liu, & Yu, 2009). For example, more complex flankers can crowd more strongly than less complex flankers even if they are less similar to the target (Zhang et al., 2009). Hence, overall, crowding would be expected to be stronger in Experiment 2 than in Experiment 1.

Importantly, the tasks in the two experiments were different. In the crowding task of Experiment 1, only the central target letter was task-relevant, whereas the flankers were not. By contrast, in Experiment 2, the task was to report the entire word. For example, in the Alternating Opposite Contrast Polarity Condition in Experiment 1, a white target had to be identified while ignoring its black flankers. In the corresponding condition of Experiment 2, a central white syllable was 'flanked' to the left and right by a black syllable (in three-syllable words). However, the black syllables were task-relevant: the entire word, i.e., all syllables, had to be reported. Such task differences have been shown to modulate performance, for example when the typical uncrowding advantage of opposite compared to same contrast polarity flankers for a single (central) trigram letter became negligible (Chung & Mansfield, 2009) or was reversed (Rummens & Sayim, 2019) when reporting all three letters. Similarly, any uncrowding benefit revealed in Experiment 1 (report of a single item) would not readily be expected to have the same effect in Experiment 2 (report of all items), even if syllables were processed as wholes (Ehri & McCormick, 1998; Grainger & Ziegler, 2011). Rather, a potential improvement by uncrowding parts of a word (such as syllables) comes with the potential cost of disrupting word uniformity, thereby interfering with recognition performance (e.g., Sanocki, 1987,1988).

In the current study, performance deteriorated when syllables and non-syllabic word parts alternated in contrast polarity, the only color/luminance condition that reduced crowding in Experiment 1. Therefore, it could be that to be beneficial for word recognition, medium feature contrasts that do not change crowding are needed. However, we did test a set of feature contrasts, including the red and black condition of Bernard et al. (2014), but none of them showed any benefit for word recognition in the Congruent compared to the Uniform condition. Possibly, differences in task difficulty and task demands explain the divergent results in the current study and the one by Bernard et al. (2014). With similar word stimuli as used in the current study (i.e., high frequency words with a 1° letter size), their results revealed a negligible advantage of syllable segmentation (Bernard et al., 2014). However, they did find a large benefit of syllable segmentation for low-frequency words of smaller letter size (0.5°). Similarly, Ferrand and New (2003) revealed processing by syllables for low but not high-frequency (French) words. Hence, syllable segmentation might only improve peripheral recognition for difficult words (i.e., words of low frequency and/or smaller letter size). Importantly, peripheral word recognition in Bernard et al. (2014) required eye movements, since an artificial central scotoma (partially) covered a word upon presentation. The necessity of eye movements may have allowed participants to develop a strategy to perform the task (Bernard et al., 2014), whereas no eye movements were required in the current study, excluding a similar strategy. Finally, a benefit of syllable segmentation in French does not necessarily generalize to German. Indeed, evidence for syllabic processing has mostly been found in Romance languages with clear syllable boundaries (i.e., syllables identical in spoken and written form; e.g., French or Spanish; Àlvarez, Carreiras & Perea, 2004; but see Conrad & Jacobs, 2004, for German).

Bernard et al. (2014) argued that the facilitating effect of color-induced syllable segmentation occurred without a reduction of crowding, because congruent and incongruent words had an equal number of segments and color boundaries (e.g., two segments and one boundary in two-syllable words), but the facilitating effect was only found for the former. The absence of reduced crowding between black and red letters in our Experiment 1 could be taken to support this conclusion. However, that segmentation in crowding can be modulated without affecting performance seems to be at odds with a large number of crowding studies that showed a strong link between grouping and crowding. More specifically, strong target-flanker grouping was shown to yield worse performance than weak target-flanker grouping (Manassi, Sayim, & Herzog, 2012, 2013; Saarela et al., 2009; Sayim et al., 2008; see Herzog et al., 2015, for a review; but see Melnik, Coates, & Sayim, 2018; Sayim, Greenwood, & Cavanagh, 2014 for beneficial effects of target-flanker grouping). In crowding paradigms, strong grouping of the target with the flankers usually reflects a lack of their segmentation, while ungrouping of the target from the flankers shows the successful segmentation into subunits. Correlations of performance in crowding with other segmentation measures, such as reaction times in visual search (Sayim, Westheimer, & Herzog, 2011) and subjective judgments of target conspicuity (Saarela et al., 2009), additionally support a strong connection of crowding, grouping, and segmentation.

Such a strong connection was also suggested by the current findings. However, segmentation induced by opposite contrast polarity yielded interference when recognizing words. We suggest this interference stems from a disruption in word uniformity, and that (compulsory) segmentation is detrimental when it interferes with the task at hand. Since interference was only found for the feature contrast that reduced crowding, disrupting word uniformity might require feature contrasts that are sufficiently strong.

Whether reduced crowding at syllable boundaries affects identification of the syllables within a word is still unclear. Our results showed an improvement of performance in letter identification (uncrowding), and a deterioration of performance in word recognition (disruption of uniformity). Since syllables remain uniform when alternating feature contrasts between them, syllable recognition does not require to report items that differ in regard to the varied features. Therefore, we expect syllable crowding to have the same basic characteristics as single letter crowding and crowding of entire words (Yu, Akau, & Chung, 2012).

To conclude, our results did not reveal improved peripheral recognition performance for words consisting of syllables alternating in color and/or luminance compared to words without such alternation. To the contrary, when word parts alternated in contrast polarity, word recognition deteriorated. We suggest that the disruption of word uniformity underlies this impairment. Alternating color/luminance of neighboring syllables cannot be recommended as a strategy to improve peripheral reading performance. The same feature contrast that impaired performance in peripheral word recognition, improved performance in crowded letter identification, suggesting commonalities between uncrowding and disrupting word uniformity. Any potential beneficial effect of reduced crowding at syllable boundaries on word recognition was outweighed by disrupted uniformity.

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