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# Challenging the similarity rule of visual crowding: When detrimental clutter becomes beneficial uniformity

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## Abstract.

In real life, objects are seldomly encountered in isolation but are more often than not surrounded by other items. Context has been shown to strongly modulate whether and how objects are perceived. In visual crowding, nearby items (‘flankers’) prevent the accurate perception of a target object. One of the central crowding rules concerns its dependence on target-flanker similarity, with usually weak crowding when target and flankers differ on a given feature. For instance, the similarity rule predicts the ‘polarity advantage’: the superior identification of a crowded target when flanked by opposite rather than same contrast polarity items. The usual benefit of low target-flanker similarity is well explained by grouping: when the target is easily segmented from its flankers, such weak target-flanker grouping typically yields mild crowding. Here, in three studies, I demonstrate strong limitations to the generality of the similarity rule. In the first study, it was revealed that the usual benefit of low target-flanker similarity did not transfer to peripheral word recognition. In particular, word recognition deteriorated when word parts – either syllables or non-syllables - alternated in contrast polarity compared to words consisting of all same contrast polarity parts. In the second study, the similarity rule – typically shown with regard to a single crowded target – was reversed when multiple crowded targets were task-relevant. When neighboring trigram letters had the same versus opposite contrast polarity, performance was worse when reporting the central letter only but surprisingly superior when reporting all letters. In the third study, I show that interactions between two features - contrast polarity and orientation – can break the similarity rule of crowding. When discriminating the central line tilt within a line triplet, the usual advantage of opposite compared to same contrast polarity flankers (relative to the target) depended on flanker orientations. The polarity advantage was found with upright (||) and bidirectional (\/ or /\) flankers, but was absent with unidirectional flankers (\\ or //). Taken together, the current findings strongly challenge the generality of the similarity rule. I propose that attentional and configural factors can overcome the usual cost of strong grouping of target and flankers, revealing benefits of stimulus uniformity instead.

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# List of published manuscripts.

### Manuscript 1 (included as Chapter 2 – pp. 19-47)

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# Chapter 1:
# General Background

In everyday life, an object seldom appears in isolation, but is usually one of many items in the visual scene. Other items in the scene may often provide valuable information about a target object, and facilitate its recognition (e.g., Bar, 2004; Bar & Ullman, 1996; Biederman, 1972; Biederman et al., 1982; Hock et al., 1978). While numerous studies have indeed shown such advantageous effects of context on object recognition, surrounding items can also strongly impair our perception of an object. In visual crowding, nearby objects or 'flankers' prevent the accurate perception of a target object (Bouma, 1970; Chung et al., 2001; Coates et al., 2021; He et al., 1996; Pelli et al., 2004; Sayim et al., 2014; Sayim & Wagemans, 2017; Strasburger et al., 1991; Stuart & Burian, 1962; Toet & Levi, 1992; for reviews see Levi, 2008; Herzog et al., 2015; Strasburger et al., 2011; Whitney & Levi, 2011). For instance, when focusing on the fixation cross, the letter K is easily identified in isolation but its identification is severely impaired with an X on each side (Fig. 1). Besides letter identification (Bouma, 1970; Chung & Mansfield, 2009; Pelli et al., 2004), crowding has been suggested to limit many other perceptual tasks such as reading (Legge, Cheung, Yu, et al., 2007; Pelli et al., 2007), visual search (Gheri et al., 2007; Sayim et al., 2011; Veríssimo et al., 2021), face recognition (Farzin et al., 2009; Kalpadakis-Smith et al., 2018; Louie et al., 2007), and driving (Wolfe et al., 2020; Xia et al., 2020). Therefore, understanding crowding would greatly contribute to the comprehension of visual perception in general.

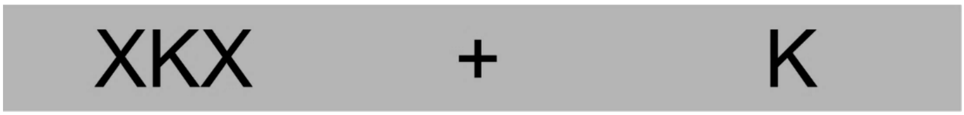


*Fig. 1.* A demonstration of the deleterious effect of crowding. When focusing on the fixation cross, identification of the individual letter 'K' on the right is straightforward. The letter K on the left is much harder to identify, as the nearby Xs strongly interfere with its recognition.

To date, several properties of crowding have been often-replicated, and obtained the status of 'rules' (see paragraph 1.1. for an overview). The current dissertation focusses on the 'similarity rule' of crowding, which predicts that crowding is usually more detrimental with high than with low target-flanker similarity (e.g., Chung & Mansfield, 2009; Kooi et al., 1994; Põder, 2007; Sayim et al., 2008). Here, I present three studies that show exceptions to this pattern, surprisingly revealing similar or better performance in conditions where the similarity rule would predict more severe crowding. These findings thus strongly challenge the generality of the similarity rule, and of key crowding properties in general. I propose that – under some conditions – attentional demands and configural cues can counteract the detrimental character of crowding.

## 1. Key properties of crowding

Crowding is strongly dependent on the spacing between target and flankers, and only takes place when flankers are located within a certain area around the target. The crowding zone has been suggested to be elliptical in shape (Toet & Levi, 1992; Bex et al., 2003; but see Livne & Sagi, 2009; Nandy & Tjan, 2009), with a larger spatial extent of crowding when flankers are positioned radially rather than tangentially (i.e. radial-tangential asymmetry; Fang & He, 2008; Livne & Sagi, 2007; Mareschal et al., 2010; Toet & Levi, 1992). Specifically, the critical spacing – i.e., the distance from which flankers no longer interfere - equals approximately half the target's eccentricity (i.e., Bouma's rule; Bouma, 1970) in the radial direction, and is estimated to be around two or three times smaller in the tangential direction (Toet & Levi, 1992). Given its proportionality on target eccentricity, crowding is especially deleterious in the peripheral visual field. Importantly, on a given axis (e.g., radial or tangential), flankers at closer compared to further distance from the target generally yield stronger crowding (e.g. Bouma, 1970; Chung et al., 2001).

Another key property of crowding – besides its dependence on spacing – concerns the similarity of target and flankers. Typically, it is harder to identify a target object when target-flanker similarity is high rather than low. For example, reporting the identity or tilt of a crowded letter was better with flankers of the opposite- compared to the same-contrast polarity as the target (polarity advantage; Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Rosen & Pelli, 2015; Sayim et al., 2008; Rummens & Sayim, 2019, 2021). This 'similarity rule' has been shown for numerous other dimensions such as color (Greenwood & Parsons, 2020; Kooi et al., 1994; Põder, 2007; Sayim et al., 2008), depth (Astle et al., 2014; Sayim et al., 2008), motion (Greenwood & Parsons, 2020), shape (Kooi et al., 1994; Nazir, 1992; Sayim et al., 2010), and complexity (Bernard & Chung, 2011; Sayim & Wagemans, 2017; Zhang et al., 2009). Besides low-level feature similarity, higher-level categorical similarity has been suggested to modulate crowding, with stronger crowding when target and flankers belonged to the same compared to a different category. In particular, a target letter was crowded more when flanked by letters than by digits, even when controlling for featural differences (Huckauf et al., 1999; Reuther & Chakravarthi, 2014). Alternatively, effects of categorical similarity on crowding may well have occurred due to response selection strategies instead of interference at higher levels of processing (Reuther & Chakravarthi, 2020).

The rules of spacing and similarity reliably predict crowding when a target has a single flanker on each side, but fall short with multi-element flankers. For instance, the offset discrimination for a black vernier was far superior when flanked by an array of ten white lines on each side than when embedded in a pattern of alternating polarity lines (Sayim et al., 2008; Manassi et al., 2012). Based on the similarity rule, no difference in performance would be expected, as the flankers nearest to the target were white in both conditions. Thus, purely local interactions cannot explain the worse performance in the alternating condition. Instead, the global stimulus configuration – formed by the target and all the flankers – determined performance. When the target stands out from its flankers – i.e. the flankers strongly group among themselves but not with the target – crowding is usually weak. Conversely, when the target groups with its flankers, crowding is strong (Banks et al., 1979; Livne & Sagi, 2007, 2010; Malania et al., 2007; Manassi et al., 2012; Rosen & Pelli, 2015; Saarela et al., 2009; Sayim et al., 2010, 2011). Subjective ratings of how much the target stood out from its flankers indeed showed that higher target conspicuity was associated with better performance on a crowding task (Malania et al., 2007; Manassi et al., 2012; Saarela et al., 2009; Wolford & Chambers, 1983). Furthermore, targets that stood out more in visual search yielded weaker crowding, when presented with the same stimulus in both tasks (Sayim et al., 2011). The strong link between grouping and crowding was also highlighted when contextual modulation itself was proposed as a measure of grouping strength (Sayim et al., 2010). Crowding and grouping show great commonalities, as both involve the integration of information over space and are spacing- and similarity-dependent. Yet, despite the substantial overlap, crowding and grouping can be distinguished, for instance, with regard to the spatial extent over which they operate. Grouping can alter the appearance of a crowded target from a distance larger than critical spacing, suggesting different spatial constraints of both phenomena (Sayim & Cavanagh, 2013).

Finally, crowding is characterized by a whole set of asymmetries. Previously, I already introduced the radial-tangential asymmetry: When located at the same distance from the target, radial flankers interfere more strongly than tangential flankers (Fang & He, 2008; Livne & Sagi, 2007; Mareschal et al., 2010; Pelli et al., 2007; Toet & Levi, 1992). Another crowding asymmetry concerns the stronger crowding in horizontal compared to vertical target-flanker arrangements (Feng et al., 2007). Furthermore, flankers are more deleterious when on the peripheral side than on the foveal side of the target (Chakravarthi et al., 2021; Chastain, 1983; Manassi et al., 2012; Petrov et al., 2007). Please note that this inward-outward asymmetry of crowding is rather counterintuitive, since outward flankers are characterized by lesser acuity yet are more impairing than its inward counterparts. Finally, crowding is weaker in the lower compared to the upper visual field (Greenwood et al., 2017; He et al., 1996, 1997; Intriligator & Cavanagh, 2001).

## 2. Crowding, ordinary masking, and redundancy masking

Crowding has been referred to as 'lateral masking' (Huckauf et al., 1999; Townsend et al., 1971; Wolford & Chambers, 1983), suggesting that crowding and visual masking have characteristics in common. Visual masking is the impaired perception of a target when another item is presented in temporal and spatial proximity (Bachmann & Francis, 2013). Thus, similar to crowding, masking occurs due to interference between multiple visual items. Furthermore, masking – as well as crowding - shows a dependence on the similarity of the target and the mask. For instance, a mask was more detrimental when similar in color or orientation to the target (Oyama et al., 1983). Despite these commonalities, masking and crowding have been suggested to be distinct phenomena. In particular, masking relative to crowding are thought to affect a different stage in the process of object recognition: while masking impairs feature detection, crowding does not hinder the detection but affects the integration of features (Pelli et al., 2004). Tilt discrimination of a target gabor among flanking gabors was severely hindered while observers could still reliably report the average orientation of all gabors presented (Parkes et al., 2001).

The authors concluded that the information of an individual crowded gabor was not lost, and thus still detected. Rather, orientations of individual gabors were compulsory combined after which the individual signal was no longer accessible. More generally, in crowding, observers still detect the presence of a crowded target, but the false or unwanted integration of detected features impairs accurate object perception. Furthermore, crowding – opposite to masking - shows a strong dependence on target eccentricity (Bouma, 1970; Pelli et al., 2007; Toet & Levi, 1992) and does not vary with stimulus size (Levi et al., 2002; Strasburger et al., 1991).

Appearance-based methods have been used to investigate how a crowded target looks like to an observer, and often revealed 'omission errors', with observers reporting fewer elements than actually presented (Coates et al., 2017; Melnik et al., 2021; Sayim & Taylor, 2019; Sayim & Wagemans, 2017). Omission errors seem to indicate a failure of detection, suggesting that masking may contribute to the impaired perception of crowded displays. A particularly strong case of omission errors occurs in 'redundancy masking' (Sayim & Taylor, 2019; Taylor & Sayim, 2020; Yildirim et al., 2019, 2020, 2021), when one (or multiple) of several identical items is (are) lost. For instance, observers often only report two items when presented with three identical lines (Yildirim et al., 2019, 2020, 2021) or letters (Sayim & Taylor, 2019; Taylor & Sayim, 2020). Similarly, identical features of adjacent letters were frequently omitted (Coates et al., 2019). Substantial overlap was found between properties of crowding and redundancy masking, as both showed radial-tangential asymmetry and a dependency on both spacing and regularity (Yildirim et al., 2020). However, in the same study by Yildirim and colleagues (2020), differences between crowding and redundancy masking were revealed as well, as redundancy masking was characterized neither by upper-lower asymmetry nor by a jumbled percept.

## 3. Theories of crowding

Several explanations for crowding have been proposed, but none of them are without shortcomings. Pooling models – a popular class of crowding models – are rooted in classical models of object recognition, processing features in a feedforward and hierarchical manner (e.g. DiCarlo et al., 2012; Hubel & Wiesel, 1962; Riesenhuber & Poggio, 1999; Serre et al., 2007). Neurons with small receptive fields in the early visual cortex detect simple features (e.g. edges or lines). The output of these low-level neurons is then combined or 'pooled', allowing for the detection of more complex features (e.g. shapes or objects) by neurons with larger receptive fields in higher visual areas. Crowding would then occur due to the pooling of detected target and flankers features within low-level receptive fields. More generally, pooling models largely converged to two-stage models, involving an unimpaired detection of features (detection stage) which are then erroneously integrated (integration stage). Pelli and colleagues (2004) describe crowding as 'excessive feature integration': As the area over which detected features are pooled is too large to contain the target features only, flanker features fall within the integration field as well, yielding an inaccurate percept.

Typically, pooling models predict target-flanker interactions to be local, detrimental, and low-level. However, many exceptions to these characteristics were revealed. First, crowding does not reflect purely local target-flanker interactions, as elements outside of Bouma's region have been shown to modulate crowding (Malania et al., 2007; Manassi et al., 2013; Sayim et al., 2014). Second, pooling models predict that more relative to fewer flankers in the crowding zone yield stronger crowding. However, adding flankers have been shown to alleviate instead of enhance crowding (Livne & Sagi, 2007, 2010; Manassi et al., 2013). Indeed, when additional flankers promote grouping among flankers itself (such as when forming a Gestalt), target-flanker grouping typically weakens, and crowding is reduced (e.g. Livne & Sagi, 2007; Manassi et al., 2013; Sayim et al., 2008). Finally, crowding did not only occur with simple, low-level features or stimuli but also with high-level faces (Farzin et al., 2009; Louie et al., 2007) and objects (Pelli & Tillman, 2008; Wallace & Tjan, 2011). As many predictions were refuted, simple pooling models have been largely dismissed.

'Simple' pooling models are object-based, combining a small number of object features via an averaging process (e.g. Greenwood et al., 2009; Parkes et al., 2001). By contrast, more 'complex' pooling models such as TTM are not restricted to objects (Rosenholtz et al., 2019). Instead, TTM computes summary statistics within local regions that tile the whole visual field, preserving a textural representation of the visual input (Balas et al., 2009; Keshvari & Rosenholtz, 2016; Rosenholtz et al., 2012, 2019). Although TTM was able to predict performance in a number of crowding tasks

(Keshvari & Rosenholtz, 2016), it failed to capture configural effects of grouping (Bornet et al., 2021).

A common error in a crowding task is to report a flanker instead of the target (Chastain, 1982; Chung & Legge, 2009; Huckauf & Heller, 2002; Strasburger, 2005; Strasburger et al., 1991). Substitution models propose that substitution errors occur due to spatial uncertainty: target and flanker features, and possibly even their identities, are correctly processed but the encoding of their respective locations goes awry or is absent. However, whether a dedicated substitution mechanism is needed to explain substitution errors is debatable. For instance, TTM has been shown to predict a loss of location information for stimulus items, suggesting that pooling mechanisms may underlie substitution errors as well (Rosenholtz et al., 2019, see also Greenwood et al., 2009).

Moreover, substitution errors may well be explained by limits of selective attention, with attentional selection of a flanker instead of the target (Chastain, 1983; Strasburger, 2005). Within an attentional account, crowding occurs due to limited attentional resolution (He et al., 1996; Intriligator & Cavanagh, 2001). At too close target-flanker spacing, attentional resolution is too coarse, preventing attentional selection of the target only. Target information that was unavailable to visual awareness due to crowding was still accurately processed in the primary visual cortex, as evidenced by intact orientation-specific adaption (but see Blake et al., 2006). Since adaption is thought to take place in V1, it follows that crowding must take place at a higher level within the visual hierarchy. Therefore, He et al. (1996) linked crowding with limits of attentional resolution, which was supported – albeit indirectly – by showing that attentional resolution is characterized by the upper-lower asymmetry typical for crowding. Other evidence in favor of an attentional account was suggested by the disappearance of the polarity advantage at the temporal resolution of attention (6-8 Hz; Chakravarthi & Cavanagh, 2007) and the occurrence of a bilateral field advantage in a crowding task (Chakravarthi & Cavanagh, 2009).

## 4. Crowding, word recognition, and reading

Reading text requires the recognition of words which in their turn demand letter identification. The number of letters that can be identified on each fixation (i.e., the visual span) is limited by crowding (He et al., 2013; Pelli et al., 2007). At fixation, letters typically do not interfere, since critical spacing is typically smaller than the letter spacing. However, the critical spacing scales with eccentricity (Bouma, 1970; Pelli et al., 2004; Toet & Levi, 1992), and exceeds the letter spacing at some point in the peripheral visual field. Thus, beyond some eccentricity, letters crowd each other, and impair word recognition. In normal reading, saccades provide a work-around to crowding, as these eye movements bring previously crowded letters into the 'uncrowded window' (Pelli et al., 2007).

The typical strong crowding in the periphery is particularly problematic for reading when foveal vision is impaired. For instance, central vision loss due to age-related macular degeneration forces patients to rely heavily on peripheral vision for reading (Chung, 2020; Legge, Cheung, Chung, et al., 2007), with strong crowding resulting in poor peripheral reading performance. Any release of crowding between a word's constituting letters may therefore benefit word recognition. Chung (2002) aimed to alleviate crowding of word letters by increasing inter-letter spacing, and measured the effect on peripheral reading. Larger compared to normal letter spacing did not fasten reading speed (see also Yu et al., 2007). Enlarged letter spacing may have neutralized the potential benefit of reduced crowding by a disruption of word form and/or a decrease in visual span (Chung, 2002; Yu et al., 2007). Indeed, when increased letter spacing did neither break the word shape (all word letters were upper case) nor decreased the visual span (only short words were tested) reading speed was faster than with normal letter spacing (Latham & Whitaker, 1996).

Others have attempted to reduce crowding within words by making neighboring letters more distinct. However, peripheral reading performance did not benefit when word letters alternated in contrast polarity than when all letters had the same contrast polarity (Chung & Mansfield, 2009). Possibly, crowding was not reduced at all for words of mixed contrast polarity letters. As outlined above (see Chapter 1 - Key properties of crowding), crowding is determined by the whole target flanker configuration (e.g. Herzog et al., 2015; Manassi et al., 2012; Sayim et al., 2008). Despite the local dissimilarity between adjacent letters, all letters seemed to have grouped into a repeating pattern, yielding strong crowding (Rosen & Pelli, 2015). Moreover, Chung & Mansfield (2009) highlighted the potential role of task differences for why the usual polarity advantage did not generalize to reading. In particular, the benefit of opposite compared to same contrast polarity flankers is typically demonstrated with regard to single crowded item, and might not apply when multiple items – for instance, all letters of a word - need to be reported. In a similar fashion, training to report the central letter within a trigram reduced the spatial extent of crowding, but did not lead to improved reading speed (Chung, 2007).

By contrast, some studies did suggest that reducing similarity between letters – and the expected reduction in crowding – may benefit word recognition and reading. For instance, trigrams and words in Eido – a font specifically designed to reduce inter-letter similarity – were recognized faster than when presented in Courier New (Bernard et al., 2016). However, likely due to oculomotor challenges, this benefit did not generalize to sentence reading with a central scotoma, as indicated by the similar performance for words in Eido and Courier New. Furthermore, when recognizing words with a central scotoma, better performance was revealed for words of syllables alternating in color compared to words where non-syllabic word parts alternated in color and uniform words (Bernard et al., 2014). Taken together, reducing the similarity between word parts did not affect word recognition in some studies while benefitting performance in other studies. Hence, how attempts to alleviate crowding within words affect word recognition and reading remains hard to predict.

## 5. Thesis Objectives

The present thesis probes the generality of the similarity rule - the usually weaker crowding with low compared to high target-flanker similarity. The similarity rule was predominantly revealed with a standard crowding paradigm: Observers are asked to report a single item surrounded by task-irrelevant flankers, while target-flanker similarity is varied on a single feature dimension. Here, I investigate whether the validity of the similarity rule is constrained by the characteristics inherent to typical crowding tasks.

As there is no benefit in processing the flankers, optimal performance in a standard crowding task should entail attentional selection of the single target only. However, it remains unclear whether the usual benefit of low similarity between neighboring items still applies when attentional selection of multiple instead of single crowded item is needed. To this aim, I investigated the validity of the similarity rule under broad attention, with tasks requiring selective attention to include multiple crowded items. In the first study (Chapter 2), I examined whether the usual benefit of low target-flanker similarity transferred to peripheral word recognition. Most studies that investigated the effect of crowding on reading performance aimed to reduce crowding of single letters. Since - beyond letters - syllables have been proposed as important units for word recognition (Ferrand & Segui, 2003; Stenneken et al., 2007), I was interested in whether reducing the similarity between syllables improved peripheral word recognition. In the second study (Chapter 3), I tested whether the similarity rule – typically revealed with regard to a single target object - generalizes to tasks with multiple crowded targets. In three experiments, I examined the effect of a typical target-flanker similarity manipulation, i.e. opposite versus same contrast polarity, when reporting a single or all stimulus items (Experiment 1: letters; Experiment 2: rotated Ts; Experiment 3: tilted lines).

Studies investigating the effect of target-flanker similarity rule typically varied target-flanker similarity on a single dimension. Few studies tested the effect when the similarity between target and flankers was varied on multiple dimensions. One such study (Põder & Wagemans, 2007) revealed weaker crowding with increasing number of dimensions on which target and flankers differed, suggesting additive effects of target-flanker similarity. In the third study of this dissertation (Chapter 4), I further explored the validity of the similarity rule when target and flankers could differ on multiple features. To this aim, I measured tilt discrimination of the central line within a line triplet, while varying target-flanker similarity both in contrast polarity and orientation.

Taken together, all three studies tested the generality of the similarity rule of crowding, providing insight in which factors may make or break its validity. The first study informs us on whether the usual benefit of low target-flanker similarity transfers to peripheral word recognition when applied to syllables. The second study addresses whether the similarity rule also applies when the task requires attentional selection of multiple crowded items. The third study provides an insight into how multiple features may interact, and conjointly affect crowding. A general discussion of all findings is included in Chapter 5.

# Chapter 2:

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

**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.

## 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 & 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.

**Experiment 1: peripheral letter recognition**

Material and methods

*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.

*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.

*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/m2; 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/m2). In the Isoluminant condition, trigrams were grey and/or red of identical luminance (20.2 cd/m2). In these three conditions (Combined, Achromatic, and Isoluminant) trigrams were presented on a white background (79.1 cd/m2). In the Opposite Contrast Polarity condition, trigrams were white (79.1 cd/m2) and/or black (0.03 cd/m2), presented on a middle grey (39.6 cd/m2) 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).

**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 | – |

*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).

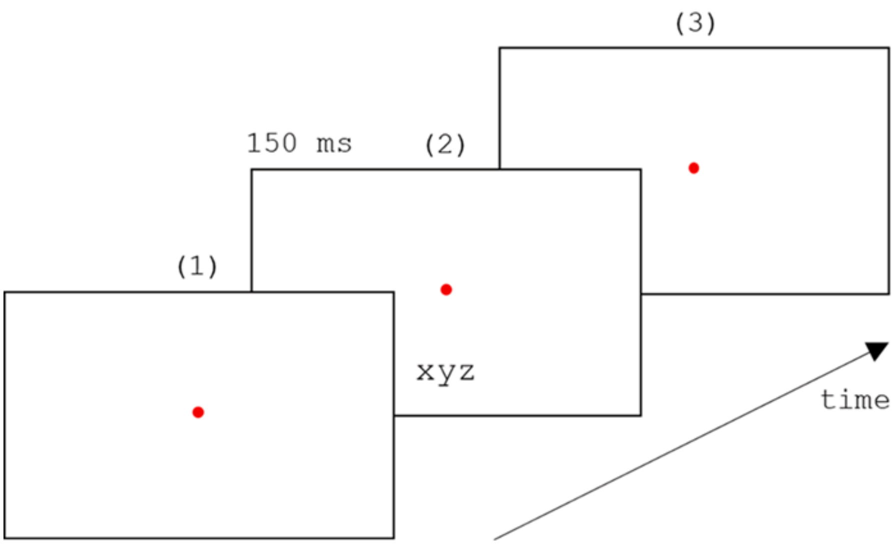

Fig. 1. Procedure of Experiment 1. (1) Participants fixated a centrally presented fixation dot. (2) Stimulus presentation was initiated by a key press. The trigram was presented for 150 ms at 8° eccentricity in the lower visual field. (3) After stimulus presentation, participants verbally reported the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

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).

*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 ($F(1,11) = 0.41$, $p = .54$), 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.

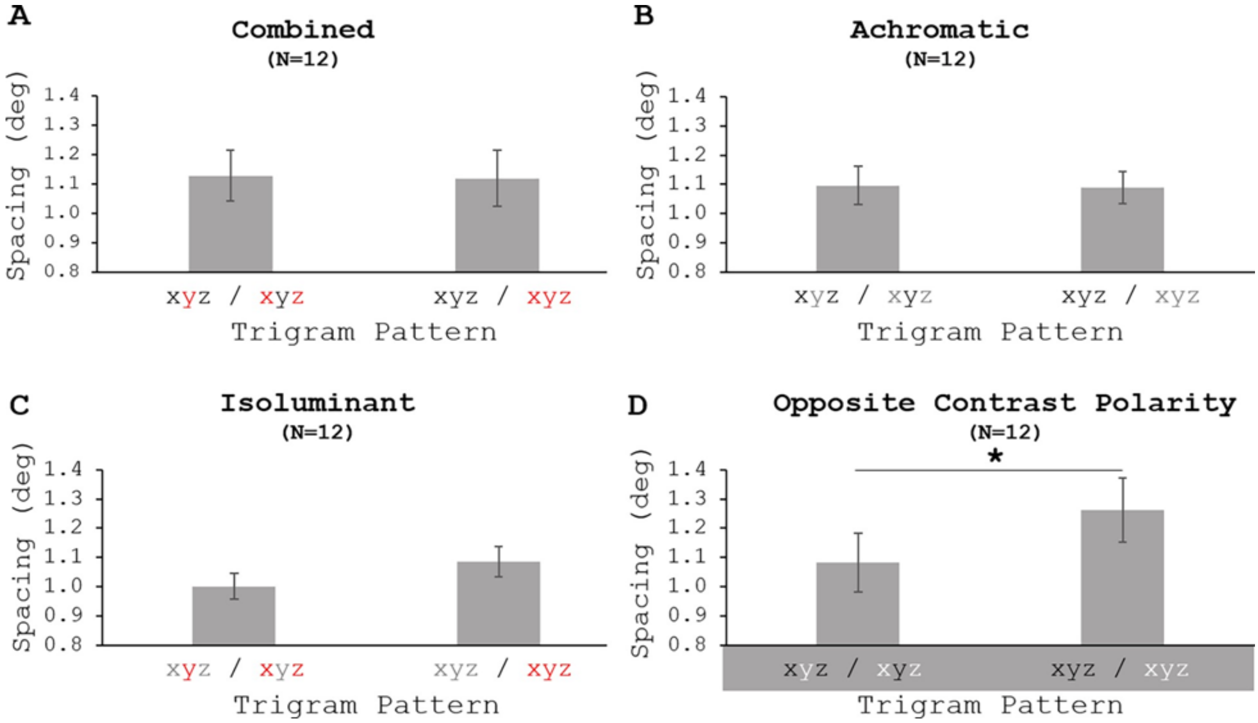


Fig. 2. Results of Experiment 1. No differences in critical spacing were found for Alternating and Uniform trigram patterns in the Combined (A), Achromatic (B), and Isoluminant (C) condition. In the Opposite Contrast Polarity (D) condition, the threshold was lower for Alternating compared to Uniform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

*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.

**Experiment 2: peripheral word recognition**

Experiment 1 showed uncrowding only when the target and the 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.

## Material and methods

### *Subjects*

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

### *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.

### *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).

*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).

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 |

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.

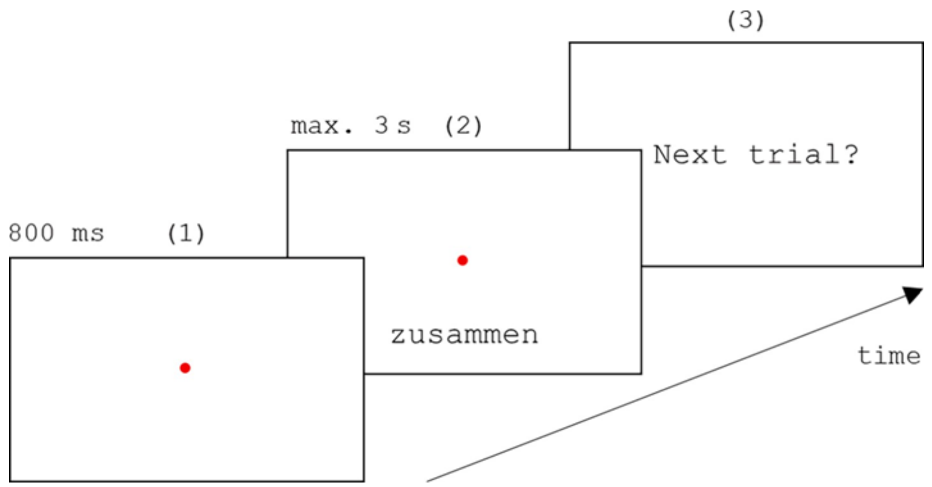


Fig. 3. The experimental procedure of Experiment 2. (1) Participants fixated the fixation dot for 800 ms. (2) Next, a word was presented at 8° eccentricity in the lower visual field for a maximum duration of 3 s. When a participant recognized a word within the 3 s timeframe, he/she pressed the response 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).

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, subject 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.

Results

*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).

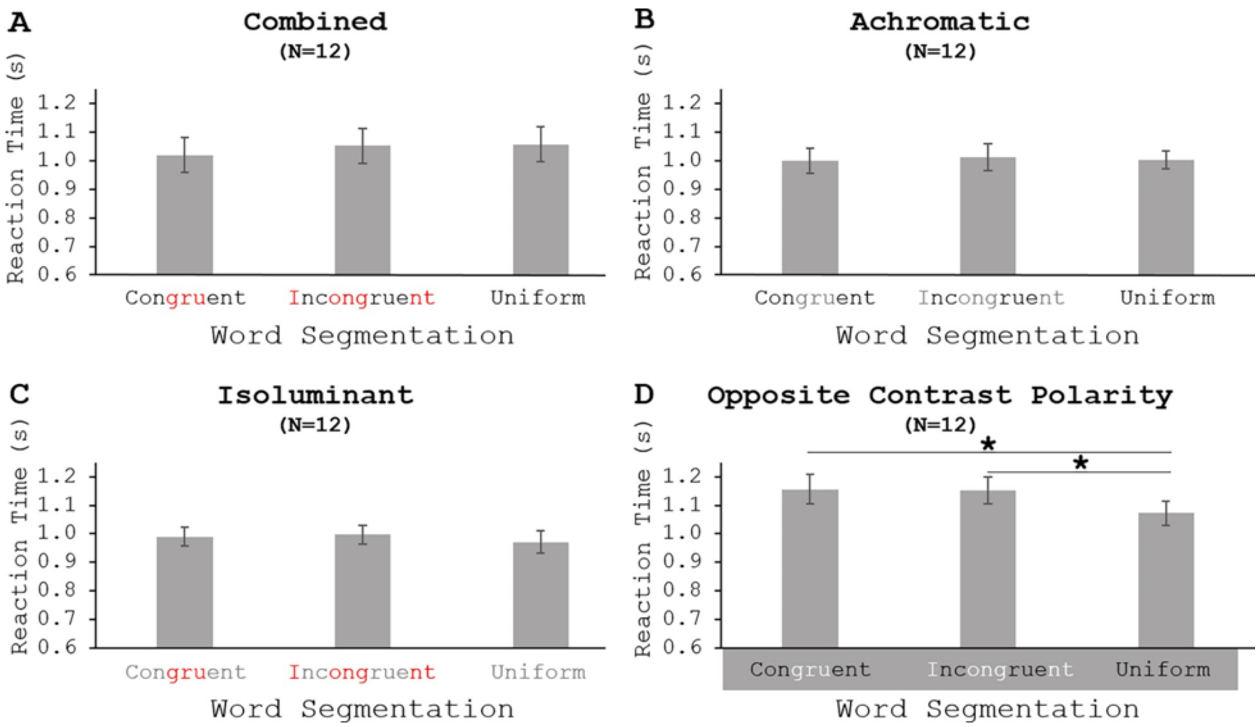

Fig. 4. Comparisons of reaction times in seconds between the different word segmentation conditions, separately for each color/luminance condition. No differences in reaction time were found between the word segmentation conditions in the Combined (A), Achromatic (B), and Isoluminant (C) condition. In 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.

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 ($F(2,22) = 1.34$, $p = .28$) 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.

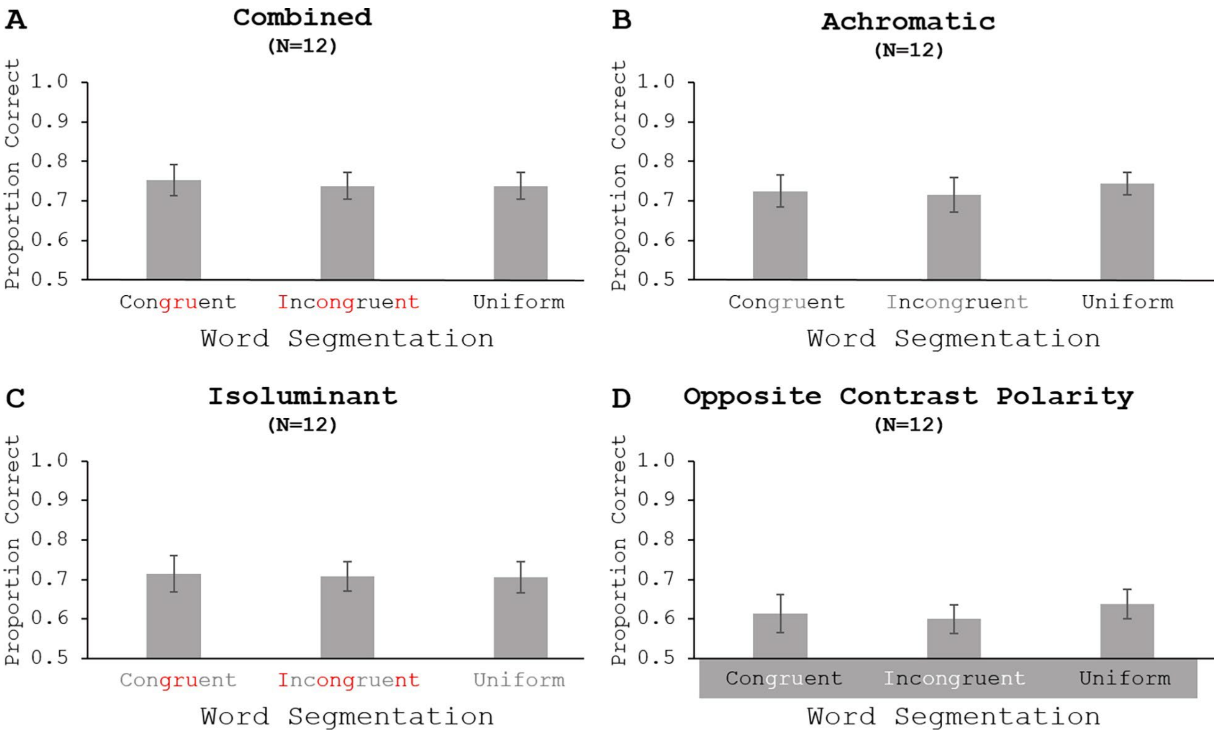


Fig. 5. Comparisons of accuracy between the different word segmentation conditions, separately for each color/luminance condition. In all color/luminance conditions (A-D), there was no difference in accuracy between word segmentation conditions. Error bars represent the mean ± 1 standard error.

*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.

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 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.

**General Discussion**

In Experiment 1, we investigated the extent to which color and luminance differences between the target and the flankers yielded un-crowding 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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# Chapter 3:

## Broad attention uncovers benefits of stimulus uniformity in visual crowding

**Abstract.** Crowding is the interference by surrounding objects (flankers) with target perception. Low target- flanker similarity usually yields weaker crowding than high similarity ('similarity rule') with less interference, e.g., by opposite- than same-contrast polarity flankers. The advantage of low target- flanker similarity has typically been shown with attentional selection of a single target object. Here, we investigated the validity of the similarity rule when broadening attention to multiple objects. In three experiments, we measured identification for crowded letters (Experiment 1), tumbling Ts (Experiment 2), and tilted lines (Experiment 3). Stimuli consisted of three items that were uniform or alternating in contrast polarity and were briefly presented at ten degrees eccentricity. Observers reported all items (full report) or only the left, central, or right item (single-item report). In Experiments 1 and 2, consistent with the similarity rule, single central item performance was superior with opposite- compared to same-contrast polarity flankers. With full report, the similarity rule was inverted: performance was better for uniform compared to alternating stimuli. In Experiment 3, contrast polarity did not affect performance. We demonstrated a reversal of the similarity rule under broadened attention, suggesting that stimulus uniformity benefits crowded object recognition when intentionally directing attention towards all stimulus elements. We propose that key properties of crowding have only limited validity as they may require a-priori differentiation of target and context.

## Introduction

In real-world settings, the amount of visual information is often overwhelming. Selective attention helps to prioritize information in the visual environment that is most relevant to current behavioral goals, while ignoring distracting information[1]. Observers' deployment of attention can thus strongly alter the effect of irrelevant information on performance in many visual tasks. For instance, visual crowding, i.e. the interference of task- irrelevant close-by items (flankers) with object perception[2-8] (for reviews see[9-12]), has been shown to depend on the spatial allocation of attention. When a pre-cue indicated the location of a crowded target, identification was enhanced relative to a no-cue condition[13-17]. These findings were attributed to observers' deployment of spatial attention, with reduced crowding when attention was focused around a limited region. Benefits of focused attention were also revealed when unilateral compared to bilateral stimulus presentation yielded weaker crowding[18]. Furthermore, attention has been suggested to underlie one of the key characteristics of crowding, i.e., its inward-outward anisotropy, where a peripheral flanker interferes more strongly with target perception than a foveal flanker. Inward-outward anisotropy was observed when attention was focused around a fixed target location, but disappeared when attention was diffused over several possible target locations19. In contrast, other studies did not reveal similar modulations of crowding by spatial attention, revealing that neither precuing the target location20,21 nor varying attentional focus affected crowding[22]. Hence, effects of spatial attention on crowding are equivocal. In the current study, we aim to further clarify the link between attention and crowding.

Crowding is characterized by a number of often-replicated properties, which have obtained the status of 'rules'[23-26]. One of the central rules of crowding is its dependence on target-flanker spacing. The critical spacing—the distance at which radially positioned flankers start to impair performance—has often been estimated to be about half the target's eccentricity ('Bouma's law'[2]). Within Bouma's range, flanker interference is usually more severe at smaller than at larger distances from the target[27]. Another key property of crowding is its depend- ence on the similarity between the target and flankers, with flankers that are more similar to the target typically yielding stronger crowding than less similar flankers (e.g.,[27,33,36,39]). Exemplary for the 'similarity rule' is the usually better identification of a crowded letter with flanking letters of opposite compared to same contrast polarity (i.e., the 'polarity advantage'[28-32]). Similarly, crowding decreased when targets and flankers differed in binocular disparity[28,33,34], color[28,34-36], orientation[37-39], or shape[20,28,40]. Furthermore, when target-flanker similarity varied on multiple dimensions (color, spatial frequency, and orientation), crowding weakened as the number of feature dimensions on which target and flankers differed increased[41]. Target-flanker similarity was also suggested to operate at a higher, categorical level: Crowding of a target letter was more severe when flanked by letters than by numbers[42], even when featural differences were controlled for[43] (but see[44]).

However, neither similarity nor spacing between the target and its immediate flankers reliably predict crowding strength. For example, when measuring offset discrimination for a black vernier flanked by ten lines on each side, performance was superior with uniform white compared to alternating white and black flankers[34]. Importantly, the innermost flankers (to the left and right of the black target) were white in both conditions, suggesting that performance depended on the global stimulus configuration (i.e., target and flanker arrays) rather than local context (i.e., target and innermost flankers). The results were attributed to target-flanker grouping: When the flankers on each side of the target grouped amongst each other but not with the target, the target "stood out" from the flankers, yielding superior performance compared to when the target grouped with the flankers and did not stand out. Importantly, a few studies quantified target-flanker grouping with additional measures, complementing the crowded identification or discrimination tasks. In particular, subjective measures of target conspicuity were shown to predict crowding strength: Targets that were rated to stand out more strongly from the flankers were also less crowded[45,46]. Similarly, objective measures of how much a target stood out from the flankers have been shown to predict performance in crowding tasks: Targets that 'popped out' in a visual search task were less crowded in a discrimination task with the same stimuli (and known target location)[13,47]. Finally, contextual modulation itself has even been proposed as a measure of grouping strength, suggesting good (bad) performance in a crowding task to be indicative of weak (strong) target-flanker grouping[40]. In general, the rule of target-flanker grouping typically predicts more severe crowding when target and flankers form a coherent perceptual group ('strong grouping') than when the target can be easily segmented from its flankers ('weak grouping')[34,35,45,48,49] (see[9] for a review).

Limitations to the generality of Bouma's rule were suggested by, for instance, its dependence on the density of the display[25,50]. While Bouma's rule applied in sparse displays, crowding in densely cluttered displays seemed to depend only on the target's 'nearest neighbors', i.e., those flankers that were within a radius far smaller than Bouma's range. Furthermore, items at larger than critical spacing have been shown to modulate crowding[48,51], and the presence of more versus less flankers within Bouma's range can also alleviate—instead of increase—crowding[35,45,48]. More recently, clear exceptions to the rules of spacing, similarity, and grouping were demonstrated. Melnik and colleagues[52] revealed weaker instead of the usual stronger crowding at smaller than at larger target-flanker spacing when the target and a flanker combined into a configuration with a salient emergent feature. In particular, the typical effect of target-flanker spacing did not hold when a central target chevron was flanked by four chevrons, one of which formed a diamond-like shape with the target or was of the same orientation as the target. Thus, at close target-flanker distance, the gain in task-relevant information provided by the emergent feature of the target-flanker combination (i.e., closure or translational symmetry) seems to have counteracted the usually stronger crowding with closer than more distant flankers. Furthermore, emergent features were suggested to override the similarity rule of crowding. In a recent study, tilt identification (left- or rightward from the vertical) of the central line within a line triplet with unidirectional flankers (\\ or //) was similar with opposite- compared to same-contrast polarity flankers[53]. The absence of the polarity advantage was further investigated with an odd-quadrant task, revealing easier discrimination between uniform compared to alternating line triplets with unidirectional flankers (e.g., \\\ and \/\). These findings suggested that emergent features benefitted performance for uniform triplets more than for alternating triplets, counteracting the typically strong crowding between same-contrast polarity lines and enabling a similar performance level as with opposite-contrast polarity flankers. Similarly, emergent features were attributed a key role in the inversion of the similarity rule when observers were more accurate at identifying a diamond shape among highly similar diamond flankers compared to flankers consisting of dissimilar Xs[23]. Taken together, the violations of basic crowding rules suggest that strong grouping can also benefit performance by enhancing the availability of task-relevant information, enabling similar or even better performance compared to weak target-flanker grouping.

The effect of target-flanker grouping—either deteriorating or improving performance—thus seems contingent on task-relevant information provided by flankers when combined with the target. Specifically, strong target- flanker grouping may hinder selective attention towards the target only, and promote unintentional processing of the flankers. When context is uninformative on target identity, such unintentional processing of flankers has been suggested to interfere with target recognition in peripheral crowding experiments as well as in foveal flanker tasks (e.g.[34,54–56]). However, when strong grouping instigated the processing of informative (but otherwise task-irrelevant) flankers or target-flanker combinations, performance in crowding tasks was equal or better than when grouping was weak[23,52,53]. Hence, in order for conventional crowding rules to hold, it may be a prerequisite that the involuntary processing of flankers—under strong target-flanker grouping—does not enhance the availability of task-relevant information. As attention is ideally directed towards the single target item but not the surrounding items, optimal performance in typical crowding tasks would require rather narrow attention. In contrast, many tasks in real-world settings require broader attention as targets often are not pre-defined and usually more than one item is task-relevant. Previous studies suggested that effects of target-flanker similarity may be different when attention needs to be broadened to multiple task-relevant items instead of focused on a single one only. Indeed, recognition of the central letter among all black trigram letters was better when observers had to report all three letters (full report) instead of only a single letter (single-item report)[64] (but see[65]). The validity of the similarity rule was also suggested to depend on attentional allocation, as central trigram letter recognition was superior with opposite versus same-contrast polarity flankers in single-item report but only minimally better in full report[30]. Similarly, word recognition and reading—tasks that also involve broadened attention as identification of multiple letters is required—was not enhanced when word parts alternated in contrast polarity compared to when word parts all had the same contrast polarity[30,32]. Hence, the validity of basic crowding rules may therefore be limited to the specific case in which a single visual target in peripheral clutter is pre-defined, and any benefit of broadening attention towards multiple items is absent.

In the current study, we investigated the validity of the similarity rule in the absence of any a-priori segmentation of what constitutes target and context. Specifically, we examined how broadening attention to several instead of a single crowded target modulated the effect of target-flanker similarity. In three experiments, we compared the effect of a typical target-flanker similarity manipulation, i.e., opposite versus same contrast polarity, when atten- tional selection of either a single or multiple crowded items was needed. To this end, in Experiment 1, observers were instructed to report either all three letters (i.e., full report) or a single letter (i.e., single-item report) of a letter trigram, demanding surrounding items to be processed or not. For both report types, trigram letters were either uniform (all black or white) or alternating (black and white) in contrast polarity. In Experiment 2 and 3, report type and contrast polarity were varied in the same way as in Experiment 1, but the task and stimuli differed. Specifically, we measured orientation identification accuracy for stimuli consisting of three randomly rotated Ts ('tumbling Ts', Experiment 2), and of three randomly left- or rightward tilted lines (Experiment 3).

The results of Experiment 1 revealed the typical polarity advantage in the single-item report paradigm, with superior performance for the central target when it was of opposite-contrast polarity than the flankers. However, in the full report condition, there was no benefit of alternating relative to uniform contrast polarity. Instead, the effect of stimulus uniformity was inverted, with worse performance in the alternating compared to the uniform condition. The same pattern of results was found in Experiment 2. Hence, the findings of Experiment 1 and 2 revealed an inversion of the target-flanker similarity rule of crowding. When attention was required to multiple instead of a single item, performance with uniform trigrams was superior to alternating trigrams. In Experiment 3, with tilted lines as stimuli, we observed a different pattern of results. Performance in the uniform and alternating condition differed neither when reporting a single line, nor when reporting all lines. Attentional allocation did not modulate performance with simple line stimuli.

Our findings showed that the effect of stimulus uniformity on crowded object recognition was strongly dependent on the attentional selection demanded by the task. Uniformity in the identical contrast polarity conditions was detrimental compared to irregularity in the alternating conditions when a single target was task-relevant, but beneficial when all items required processing. The similarity rule thus no longer held when selective attention was intentionally broadened to include multiple objects. The inversion of one of the central rules of visual crowding by broadened attentional allocation questions the generality of crowding rules. We propose that basic crowding rules do not apply in many real-life situations which, in contrast to typical crowding paradigms, often require broad attention as what constitutes task-relevant targets and irrelevant contexts is usually not pre-defined.

**Experiment 1: letter recognition**

**Methods.**

*Subjects.* Ten students (F = 8, M = 2) between 19 and 27 years of age participated for course credit. All participants reported normal or corrected-to-normal vision. Informed consent was obtained for 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.

*Apparatus.* Stimuli were displayed on a 21 inch CRT monitor (HP p1230, refresh rate = 110 Hz, resolution = 1152 × 864). The experiment code ran with Psychopy[59,60] on a Windows computer. Participants were seated at 57 cm from the screen using a head- and chinrest.

*Stimuli.* Stimuli were letter trigrams of three non-repeating letters, randomly drawn from the 26 letters of the alphabet. Trigram letters were all upper case and appeared in the mono-spaced Courier New font. Letters were 1 degree in size, and had a 1.4 degree (center-to-center) spacing between them. Trigrams were centered on the horizontal meridian, with the central trigram letter positioned at ten degrees in the left or right visual field. Trigrams were tested in four contrast polarity conditions (see Fig. 1A). Trigrams consisted of all black letters (0.03 cd/m2; BBB-trigrams), all white letters (79.4 cd/m2; WWW-trigrams) letters, a black central letter flanked by white letters (WBW-trigrams), or a white central letter flanked by black letters (BWB-trigrams). BBB- and WWW-trigrams were considered uniform, as all letters had the same-contrast polarity; WBW- and BWB-trigrams were considered alternating, as adjacent letters had opposite-contrast polarity. Trigrams were presented on a middle grey (39.6 cd/m2) background. For baseline measurement, a single black or white letter was presented at 10 degrees in the left or right hemifield.

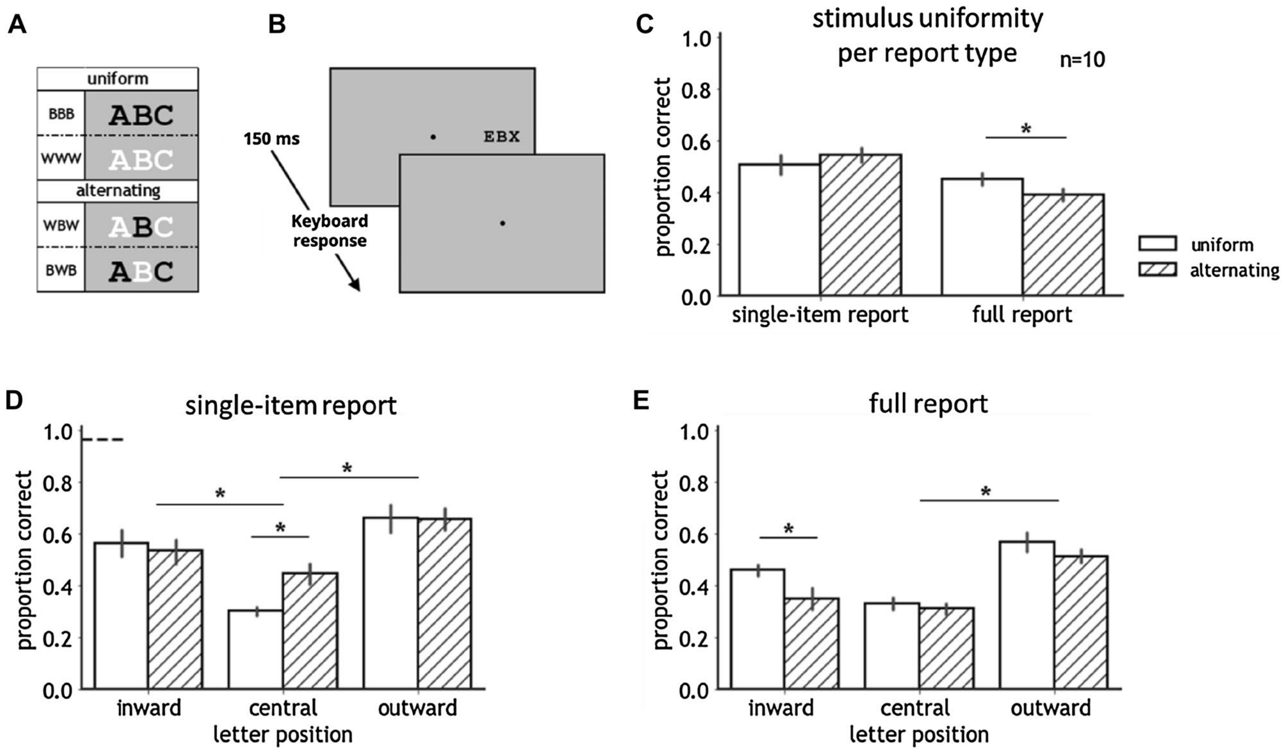


**Figure 1.** (**A**) Illustration of the letter stimuli in Experiment 1. Trigrams, either uniform or alternating in contrast polarity, consisted of three random, non-repeating letters. In uniform trigrams, all letters had the same contrast polarity (BBB- and WWW-trigrams, with B and W respectively indicating a black and white item), in alternating trigrams the contrast polarity of the central letter was opposite to its adjacent letters (WBW- and BWB-trigrams). (**B**) Time course of a trial for each report type in Experiment 1. Before the first trial of each block, participants were instructed on which letter position(s) to report. (**C–E**) Results of Experiment 1. Asterisks indicate a significant difference at the 0.05 alpha level. Error bars indicate the standard error of the mean. (**C**) Proportion correct for uniform and alternating trigrams in single-item and full report with all letter positions pooled. The interaction between stimulus uniformity and report type was characterized by no difference in proportion correct between uniform and alternating trigrams with single-item report, and worse performance for alternating compared to uniform trigrams with full

report. (**D**, **E**) Proportion correct for uniform and alternating trigrams in single-item and full report separately for all letter positions. The dashed line denotes unflanked performance. With single-item report, the polarity advantage was revealed, with better recognition of the central letter in alternating compared to uniform trigrams. With full report, performance for alternating compared to uniform trigrams was worse for the inward letter only.

*Procedure*. In Experiment 1, we measured recognition accuracy for peripherally presented letter trigrams. Report type and contrast polarity were varied. For each contrast polarity condition, participants reported either a single letter (single-item report) or all letters (full report). In the single-item report condition, at the beginning of each block, observers were instructed whether it was the left, central, or right letter that had to be reported; in full report, participants were instructed to report all three letters from left to right.

Trials were blocked by report type (single-item and full report), letter position (single-item report: inward, central, or outward; full report: inward, central, and outward) and contrast polarity condition (BBB-, WWW-, WBW-, or BWB-trigrams). Overall, there were sixteen different conditions. Observers completed all four contrast polarity conditions of a report type by letter position condition before proceeding to the next block. For example, a participant performed single central letter report for BBB-, WWW-, WBW-, and BWB-trigrams, and then completed all contrast polarity conditions in full report etc. The order of contrast polarity conditions, and report type by letter position conditions was randomized. Each block comprised 20 trials, preceded by four practice trials that were excluded from the analysis. Stimuli were randomly presented in the left or right hemifield, with each block including an equal number of trials (ten) per hemifield. In the first half of the experiment, observers executed every condition once, thus completing 16 blocks or 320 trials. In the second half of the experiment, the condition order was reversed. Additionally, observers performed four blocks of 20 unflanked trials for single black and white letters (two blocks each). Half of the participants performed the unflanked trials in the beginning and end of the experiment, and the other half completed all unflanked trials halfway. Overall, each partici- pant completed 720 trials (640 flanked and 80 unflanked trials). Due to confusions between keyboard layouts QWERTY and QWERTZ (predominantly used in Switzerland), trials with Y or Z both as target and response (i.e., 'y-z trials') were excluded for seven participants who showed a proportion of y–z confusion errors above 10 percent on y–z trials (3.4% of all trials).

The procedure of Experiment 1 is shown in Fig. 1B. Each block started with an instruction screen, inform- ing the participant about which trigram letter(s) to report. Next, a black fixation dot appeared, and remained present throughout the trial. Upon key press, a trigram was presented for 150 ms in the left or right visual field. Participants reported the perceived trigram letter(s) by pressing the corresponding keyboard key(s). An auditory feedback signal after each response provided information on registration but not accuracy.

**Results and discussion.** To investigate the effect of stimulus uniformity on the recognition of one or multiple crowded letters, the results of the BBB- and WWW-trigrams were combined (i.e., the uniform condition), and the WBW- and BWB-trigrams were combined (i.e., the alternating condition). In single-item report, there was no difference between BBB- and WWW-trigrams ($p = 0.103$), and no difference between WBW- and BWB- trigrams ($p = 0.855$). In full-report, there was no difference between the uniform contrast polarity conditions ($p = 0.434$), and a trend for worse performance for WBW-trigrams compared to BWB-trigrams ($p = 0.051$). Separately for uniform and alternating trigrams, we calculated each participant's proportion correct for each report type (single-item and full report) and letter position condition (inward, central, and outward). We conducted a repeated-measures ANOVA with accuracy (arcsine-transformed proportion correct) as dependent variable, including report type, stimulus uniformity, and letter position as within-subject variables. All post-hoc compari- sons were Tukey-tests. Main effects were revealed for all three factors: letter position ($F(2,18) = 15.01$, $p < 0.01$, $\eta 2 = 0.42$), stimulus uniformity ($F(1,9) = 5.15$, $p < 0.05$, $\eta 2 = 0.002$), and report type ($F(1,9) = 35.81$, $p < 0.001$, $\eta 2 = 0.11$).

Furthermore, our analysis showed an interaction between stimulus uniformity and report type ($F(1,9) = 9.47$, $p < 0.02$, $\eta 2 = 0.02$). All letter positions taken together, post-hoc Tukey-tests revealed lower performance for alternating compared to uniform trigrams in full report ($p < 0.02$), and no difference in single-item report ($p = 0.23$) (see Fig. 1C). Separately for single-item and full report, we tested for differences between stimulus uniformity conditions at each letter position. In single-item report, we found the typical higher accuracy for the central letter with opposite- compared to same-contrast polarity flankers ($p < 0.001$), and no difference between uniform and alternating trigrams for the other letter positions (inward: $p = 1.00$, outward: $p = 1.00$; see Fig. 1D). In full report, performance for the inward letter was worse for alternating compared to uniform trigrams ($p < 0.02$) (see Fig. 1E). With regard to the remaining letter positions, there was no difference between uniform and alternating trigrams (central: $p = 1.00$; outward: $p = 0.75$). The effect of letter position with single-item report (uniform and alternating trigrams combined) showed worse performance for the central letter compared to both flanking letters (inward: $p = 0.02$; outward: < 0.001). Proportion correct for the inward letter was lower as for the outward letter, but not significantly different ($p = 0.24$). With full report, recognition of the central letter was worse than for the outward letter ($p < 0.01$), and any other differences between letter positions were absent (central vs inward: $p = 0.57$; inward vs outward: $p = 0.11$). Additionally, our results revealed an interaction between letter position and contrast polarity ($F(2,18) = 9.59$, $p < 0.01$, $\eta 2 = 0.03$). There were no other interactions.

We also analyzed whether the two report types differed in the types of errors observers made. Specifically, we looked at two types of errors: a position error occurred when correctly reporting a stimulus letter but at a false location, and an identity error when reporting a letter not present in the trigram58. The proportion of position errors relative to the total number of errors was higher in single-item compared to full report ($F(1,9) = 22.62$, $p < 0.001$, $\eta 2 = 0.06$). Accordingly, full report had a larger proportion of identity errors compared to single-item report. The prevalence of none of the six possible positions errors differed between report types (all $ps < 0.22$).

As observers were instructed to report all letters from left to right in full report, we also analyzed whether order effects occurred. Letter position was now defined in terms of absolute position (left, central, and right) instead of position relative to fixation (inward, central, and outward). Single-item performance (uniform and alternating trigrams combined) was similar for the left letter compared the right letter ($p = 0.78$), and worse for the central letter compared to both flanking letters (both *ps* < 0.001). In full report, recognition of the left letter was superior compared to the right and central letter (*ps* < 0.001), and did not differ between the right and the central letter ($p = 0.91$).

As expected, in single-item report, recognition of the central letter was worse than of both the inward and outward letter. Superior performance for alternating compared to uniform trigrams when only reporting the central letter confirmed the similarity rule. In full report, none of the letter positions showed a benefit with oppo- site- relative to same-contrast polarity flankers. Rather, when reporting all letters, performance for alternating trigrams was worse than for uniform trigrams, mainly driven by a significant cost of opposite-contrast polarity for the inward letter position. In sum, the main finding of Experiment 1 showed an inversion of the similarity rule of crowding: alternating compared to uniform contrast polarity flankers facilitated recognition of the central item in single-item report, yet impaired performance for inward and outward letters when reporting all items.

**Experiment 2: orientation identification of tumbling Ts**

Experiment 1 revealed the usual superior recognition of a single, central item flanked by opposite- compared to same-contrast polarity flankers, but alternating polarity hindered performance when identifying all trigram letters. In Experiment 2, we investigated whether the same inversion occurred when including stimuli of similar complexity in a 4-AFC orientation task.

**Methods.**

*Subjects.* Ten participants (F = 7, M = 3) between age 20 and 25 completed the study in return for course credit. They were self-reported non-dyslexics with normal or corrected-to-normal vision, and did not participate in Experiment 1. All participants gave written informed consent.

*Apparatus and stimuli.* Apparatus was identical to Experiment 1. Stimuli consisted of three horizontally aligned rotated Ts, with each T having a unique orientation within the trigram. Rotation of a T was either 0 (upward), 90 (rightward), 180 (downward), or 270 (leftward) degrees, enabling twenty-four possible combinations overall. Each T comprised two orthogonal lines of equal length (1 degree). Adjacent Ts had a center-to-center spacing of 1.4 degrees between them, with the central T presented at 10 degrees in either the left or right visual field. As in Experiment 1, four contrast polarity conditions were included: in the uniform condition, trigrams consisted of all black (BBB-trigram) or all white (WWW-trigram) Ts, and in the alternating condition of a black central T with white flanking Ts (WBW-trigram) or vice versa (BWB-trigram) (see Fig. 2A). Luminance values of stimuli (black: 0.03 cd/m2; white: 79.4 cd/m2) and background (grey: 39.6 cd/m2) were identical to Experiment 1.

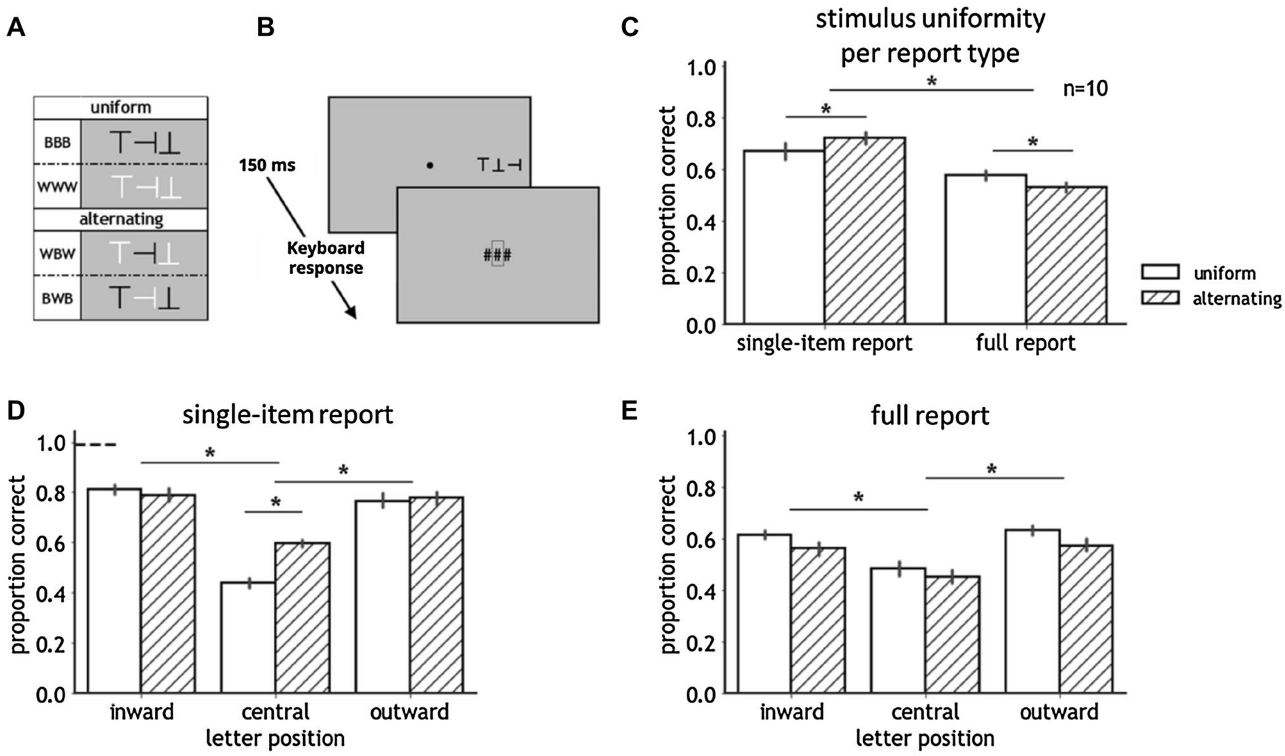


**Figure 2.** (**A**) Illustration of the stimuli of Experiment 2. Trigrams of 'tumbling Ts', either uniform or alternating in contrast polarity, consisted of three Ts of different orientation (0°, 90°,180°, or 270°). BBB, WWW, BWB, and WBW were the four contrast polarity conditions we tested, with B and W respectively representing a black and white item. (**B**) Time course of a trial with single-item report in Experiment 2. The rectangle around the placeholder ('#') indicates which letter position required reporting. With full report, the rectangle surrounded all three placeholders. Before the first trial of each block, participants were instructed on which letter position(s) to report. The rectangle and the indicated target position(s) thus remained the same throughout the block. (**C–E**) Results of Experiment 2. Asterisks indicate a significant difference at the 0.05 alpha level. Error bars indicate the standard error of the mean. (**C**) Accuracy for uniform and alternating T-trigrams in single-item and full report with all letter positions pooled. The interaction between stimulus uniformity and report type was characterized by better performance for alternating compared to uniform trigrams in single-item report, and worse performance for alternating compared to uniform

trigrams in single-item report. (**D–E**) Accuracy for uniform and alternating T-trigrams in single-item and full report separately for each letter position. The dashed line denotes unflanked performance. With single-item report, the polarity advantage was revealed: Recognition of the central letter was better with opposite- compared to same-contrast polarity flankers. With full report, none of the letter positions showed a significant effect of stimulus uniformity.

*Procedure*. Participants reported the orientation of either a single or all Ts (report type) of a uniform or alter- nating (stimulus uniformity) T-trigram. As in Experiment 1, report type and contrast polarity were varied. Trials were blocked in an identical manner to Experiment 1, with participants completing 32 blocks of flanked trials and 4 blocks of unflanked trials. The overall number of trials was again 720. The procedure of Experiment 2 is depicted in Fig. 2B. Similar to Experiment 1, observers were informed on which letter position(s)—either one (left, central, or right) or all Ts (left to right)—required reporting before each block. Stimuli were presented for 150 ms. After stimulus presentation, participants responded with the arrow keys (up, down, left, or right), indicating the orientation of the target T(s). The procedure differed in two ways to Experiment 1. First, after stimulus presentation, the fixation dot was replaced with three placeholders (# # #). A rectangle around either one or all three placeholders repeated which position(s) to report in the current trial. Following the oberver's response, the relevant placeholder was replaced with a T of the selected orientation. Second, given the visual feedback, no auditory feedback was provided.

**Results and discussion.** Data were analyzed identically to Experiment 1. Neither in single-item report ($p$ = 0.28) nor in full report ($p$ = 0.97), we found different performances for uniform BBB- compared to WWW- trigrams. There was also no difference between WBW- and BWB-trigrams (single-item report: $p$ = 1.0; full report: $p$ = 0.97). Hence, we combined the results of the BBB- and WWW-trigrams (i.e., the uniform condition), as well as those of WBW- and BWB-trigrams (i.e., the alternating condition). With accuracy (arcsine-transformed proportion correct) as dependent variable, a repeated-measures ANOVA including report type, stimulus uni- formity, and letter position as within-subject variables revealed main effects of letter position ($F(2,18) = 55.96$, $p < 0.001$, $\eta2 = 0.42$) and report type ($F(1,9) = 110.21$, $p < 0.001$, $\eta2 = 0.26$). Performance was worse in full com- pared to single-item report.

The effect of stimulus uniformity depended on report type ($F(1,9) = 23.70$, $p < 0.001$, $\eta 2 = 0.03$): accuracy was higher for alternating compared to uniform trigrams in single-item report ($p = 0.04$), yet lower when reporting the orientations of all Ts ($p = 0.04$) (see Fig. 2C). In single-item report, the advantage of alternating over uniform contrast polarity was driven by performance for the central letter (central letter: $p < 0.001$; inward and outward letter: $p = 1.0$) (see Fig. 2D). The lower accuracy for alternating versus uniform contrast polarity in full report was due to absolute differences in the same direction at all letter positions (see Fig. 2E). Overall (uniform and alternating trigrams combined), single-item report was worse for the central letter compared to both flanking letters (inward: $p < 0.001$; outward: $p < 0.001$), and did not differ between inward and outward letters ($p = 0.82$). With full report, our findings showed a similar pattern with worse performance for the central compared to both flankers (inward: $p < 0.01$; outward: $p < 0.001$), and no difference between the inward and outward T ($p = 0.99$). The interaction between report type and letter position ($F(2,18) = 13.49$, $p < 0.001$, $\eta 2 = 0.07$) was primarily due to better performance in single-item compared to full report for both inward ($p < 0.001$) and outward Ts ($p < 0.001$), with similar accuracies between report types for the central T ($p = 0.47$). Additionally, our findings revealed interactions between contrast polarity and letter position ($F(2,18) = 11.29$, $p < 0.001$, $\eta 2 = 0.02$), and between all factors of the model ($F(2,18) = 7.76$, $p < 0.01$, $\eta 2 = 0.01$).

The error analysis showed that the proportion of position errors relative to all errors was higher with single- item compared to full report ($F(1,9) = 61.72$, $p < 0.001$, $\eta 2 = 0.07$). Full report was thus characterized by a larger proportion of identity errors compared to single-item report. With uniform and alternating trigrams combined, outward letters were perceived more often at the central location in single-item compared to full report ($p < 0.02$), and proportions of the remaining position errors did not differ between report types (all *ps* < 0.36). This pattern differed between uniform and alternating contrast polarity conditions, as indicated by a three way interaction: $F(5,45) = 3.34$, $p < 0.02$, $\eta 2 = 0.03$).

The analysis of order effects was performed identically to Experiment 1. Single-item performance (uniform and alternating trigrams combined) was similar for the left and right letter ($p = 0.941$), and worse for the central letter compared to both flanking letters (both *ps* < 0.001). In full report, recognition of the left letter was superior compared to the right and central letter (*ps* < 0.001), and did not differ between the right and the central letter (*p* = 0.97).

In single-item report, our data revealed the expected lower performance for the central compared to both flanking Ts. Accuracy did not differ between inward and outward Ts. Similar to Experiment 1, our main finding in Experiment 2 revealed an inversion of the similarity rule of crowding. In single-item report, the similarity rule held: recognition of the central T was superior with adjacent Ts of opposite- compared to same-contrast polarity. However, when all Ts required reporting, worse accuracy for alternating compared to uniform stimuli revealed a violation of the rule of similarity. As in Experiment 1, the findings of Experiment 2 suggested a strong dependence of the effect of target-flanker similarity on report type.

**Experiment 3: orientation identification of tilted lines**

Both Experiment 1 and 2 showed an inversion of the similarity rule of crowding. Specifically, alternating con- trast polarity improved performance for a single, central target, but deteriorated performance when reporting all stimulus items. In Experiment 1 and 2, stimuli were letters, i.e., complex targets that required integration of multiple features. In Experiment 3, to probe if stimuli of lesser complexity are subject to the same inversion of the target-flanker similarity rule of crowding, we measured orientation identification for tilted lines.

**Methods.**

*Subjects.* Twelve subjects (F = 8, M = 4) between 20 and 31 years of age participated either for course credit or monetary remuneration. All reported to have normal or corrected-to-normal vision, and gave written informed consent. One subject also participated in Experiment 2.

*Apparatus and stimuli.* Apparatus was identical to Experiment 1 and 2. Stimuli comprised three horizon- tally arranged, near-vertical lines that were centered on the horizontal midline. Lines were 0.7 degrees long, 0.1 degrees wide, and had 0.35 degrees spacing between them. Each line was randomly tilted 0.1 degrees to the left or right, resulting in eight tilt combinations. Contrast polarity was varied in an identical fashion to Experiments 1 and 2, including uniform BBB-and WWW-triplets and alternating BWB- and WBW-triplets (see Fig. 3A). Luminance values were the same as in the previous experiments (black: 0.03 cd/m2; white: 79.4 cd/m2; grey background: 39.6 cd/m2).

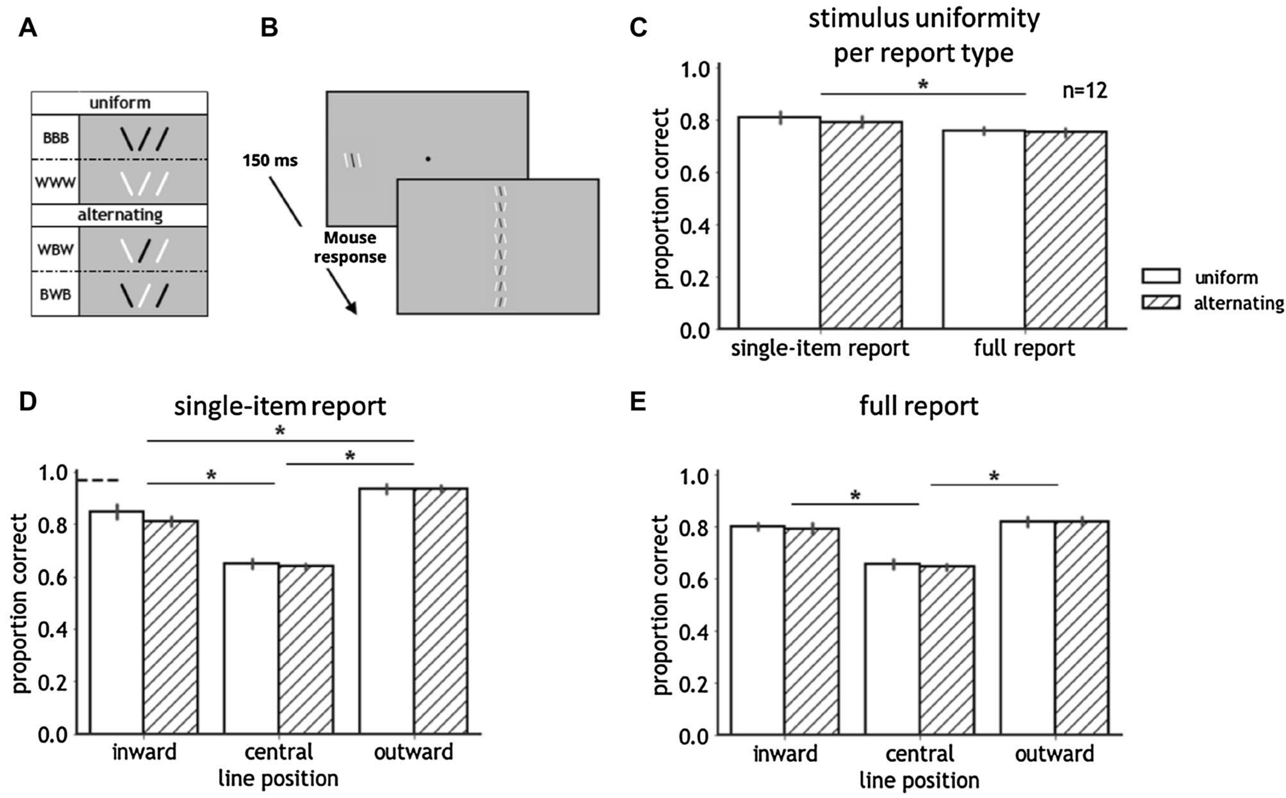


**Figure 3.** (**A**) Illustration of the stimuli of Experiment 3. Stimuli, either uniform or alternating in contrast polarity, consisted of three lines, each tilted to the left or right (eight possible configurations). BBB, WWW, BWB, and WBW refer to the contrast polarity conditions ('B' for 'black' and 'W' for 'white' item). (**B**) Time course of a trial for each report type in Experiment 3. Before the first trial of each block, participants were informed about which line position(s) to report. The lower screen shows the eight response options with full report. With single-item report, only two response options were presented. (**C–E**) Results of Experiment 3. Asterisks indicate a significant difference at the 0.05 alpha level. Error bars indicate the standard error of the mean. (**C**) Accuracy for uniform and alternating lines in single-item and full report with all line positions pooled. (**D**, **E**) Accuracy for uniform and alternating lines in single-item and full report separately for each line position. The dashed line denotes unflanked performance. The polarity advantage was absent, as the single-item report of the central letter was not superior for alternating compared to uniform trigrams. Both with single-item and with full report, none of the letter positions was affected by stimulus uniformity.

*Procedure*. As in Experiment 1 and 2, the independent variables were contrast polarity and report type. We measured accuracy of tilt identification for BBB-, WWW-, WBW-, and BWB-triplets. Participants reported the left- or rightward tilt of one of the three lines (left, central, or right) in single-item report or all three lines in full report. The experimental procedure (see Fig. 3B) was similar to Experiment 1 and 2. At the beginning of each block, an instruction screen informed participants on the line position(s) of which to report the orientation(s). Next, a central fixation dot appeared, and participants initiated the brief stimulus presentation with spacebar. Different from Experiments 1 and 2, the presentation duration was set at 100 ms instead of 150 ms (based on pilot experiments). Furthermore, the response format differed from Experiment 1 and 2. After stimulus presentation, all response options (2-AFC or 8-AFC in single-item and full report, respectively) were displayed one beneath the other, and centered on the screen. Participants responded by selecting the perceived line orientation(s) with a mouse-click. Blocking and counterbalancing was identical to both previous experiments, but the number of trials differed. Participants performed 32 flanked (16 trials each; each tilt combination tested twice) and 4 unflanked blocks (20 trials each), and thus completed 592 trials overall.

*Results and discussion*. For both report types, performance differed neither between uniform BBB- and WWW-triplets (single-item report: $p = 1.0$; full report: $p = 0.97$) nor between alternating BWB- and WBW-triplets (single-item report: $p = 0.96$; full report: $p = 0.87$). A repeated-measures ANOVA with accuracy (arcsine transformed proportion correct) as dependent variable, and stimulus uniformity, report type, and line position (inward, central, outward) as within-subject factors revealed main effects of line position ($F(2,22) = 140.39$, $p < 0.001$, $\eta2 = 0.63$) and report type ($F(1,11) = 24.40$, $p < 0.001$, $\eta2 = 0.07$). Accuracy when reporting all items was worse than in single-item report (see Fig. 3C). Our analysis revealed an interaction between report type and line position ($F(2,22) = 0.68$, $p < 0.001$, $\eta2 = 0.08$). With single-item report (uniform and alternating triplets combined), identification of the central line was worse compared to both flanking lines (inward: $p < 0.001$; outward: $p < 0.001$), and performance for the inward line was inferior to the outward line ($p < 0.001$). With full report, accuracy for the central line was lower than for both the inward ($p < 0.001$) and the outward line ($p <$

0.001). Performance did not differ between the inward and outward line ($p = 0.87$). Any other interactions were absent. Due to the 8-AFC response format in the full report condition, observers were not instructed to report all lines from left to right. Therefore, we did not include an analysis of order effects. Given the presence of repeating line tilts within triplets, neither position nor identification errors were analyzed.

As anticipated, with single-item report, we found worse recognition for the central line compared to both other line positions. Inferior accuracy for inward compared to outward lines indicated inward-outward anisotropy. Surprisingly, we did not find typical uncrowding by opposite-contrast polarity: accuracy for a single central line did not improve with alternating compared to uniform contrast polarity flankers (see Fig. 3D). Contrary to both previous experiments, when identifying all stimulus items, a benefit of uniform compared to alternating contrast polarity was absent (see Fig. 3E). The same experiment, except for a slightly increased presentation duration and line spacing (150 ms and 0.5 degrees respectively) yielded the exact same pattern of results. In brief, the results of Experiment 3 deviated from both previous experiments: performance in single-item report did not replicate the similarity rule of crowding, and there was no inversion of the rule in full report.

**General discussion**

The majority of crowding studies uses single-item report paradigms, measuring performance when attentional selection of a single target among task-irrelevant flankers is required. These investigations have revealed, amongst other characteristics, the target-flanker similarity rule of crowding. High target-flanker similarity usually yielded stronger crowding than low target-flanker similarity, which has been shown for a broad range of features, such as color[28,34-36], depth[28,33,34], and contrast polarity[28-32]. In typical single-item report paradigms, given the task- irrelevance of the flanking items, performance should benefit (or at least not deteriorate) when not attending the target's surrounding objects. However, especially with small target-flanker spacings, selective attention towards the target alone may be impaired, and both target and flankers may be compulsory processed together instead[3,61]. In contrast to typical crowding tasks, not attending to contextual items in real-world settings may be less optimal as a priori distinctions between target and context are frequently absent, and surrounding items often carry information about object identity (for reviews see[62-66]). For example, informative contexts have been shown to reduce crowding[67], as indicated by improved identification of a peripheral object with increasing availability of its typical real-world context. Hence, while optimal performance in crowding tasks usually requires attentional selection of a single item, attentional selection of multiple items may be more appropriate in real-world tasks. Here, we probed the validity of the target-flanker similarity rule when the processing of either a single or multiple crowded items was required. In particular, we investigated whether reduced similarity between neighbouring items would still benefit crowded object recognition in a full report paradigm where broadened attention towards multiple items was required.

Our results revealed an inversion of the similarity rule of crowding. When reporting the central letter only, performance was better for alternating versus uniform letters (Experiment 1 and 2). In full report, opposite- contrast polarity deteriorated crowded letter recognition, with worse performance for alternating compared to uniform polarity letters. In Experiment 3, an orientation discrimination task with tilted lines did not reveal a similar inversion. Instead, performance for uniform and alternating lines was similar at all line positions, both when reporting all line orientations and when reporting the orientation of a single line only. In sum, when decreased target-flanker similarity enhanced performance for a single, central item, reduced similarity between adjacent items was costly when reporting all items.

In Experiment 1 and 2, our findings revealed that report type modulated the effect of target-flanker similarity on performance. Both for letter (Experiment 1) and T-trigrams (Experiment 2), recognition of the central letter was better for alternating compared to uniform trigrams with single-item report, replicating the polarity advantage. However, when reporting all letters, any benefit of alternating over uniform contrast polarity was absent. Instead, our result showed worse performance for alternating compared to uniform trigrams in full report, suggesting benefits of uniformity when all letters were task-relevant. These results are in line with an earlier crowding study that revealed better identification of a central trigram letter when observers had to report all letters instead of the central letter only, suggesting that high-target flanker similarity is less deleterious with full compared to single-item report[57]. Furthermore, with full report, data from a small sample (n = 2) suggested that crowding of the central trigram letter was only minimally stronger when adjacent letters had the same- compared to opposite-contrast polarity flankers[30]. Alternating relative to uniform contrast polarity improved segmentation of a trigram into its constituting letters, but, despite a reduction of crowding, deteriorated performance when the whole stimulus had to be reported. Previous findings have revealed similar uniformity advantages in tasks that also required the identification of multiple letters. For example, we recently showed faster recognition of same polarity words compared to words of which word parts—either syllables or non-syllables—alternated in contrast polarity[32] (but see[68] for beneficial effects of syllable segmentation by color). Deleterious effects of disrupted compared to intact word uniformity were also shown when letters alternated in lower and upper case[69-73], size[72] or color[73]. Tasks such as face recognition[74], vernier offset discrimination[75], and shape detection[76] have been shown to benefit from uniformity as well. Hence, in a broad range of tasks, segmenting the initial target object into multiple objects impaired perception of the whole. Here, we showed costs of improved segmentation in a crowding task, questioning the generality of crowding rules.

Experiment 1 and 2 revealed better full report performance when trigrams were uniform, and thus not segmented by alternating contrast polarity. We suggest that the same-contrast polarity letters of uniform trigrams likely formed a more coherent perceptual object than the opposite-contrast polarity letters in alternating trigrams[77]. In foveal vision, experiments on 'object-based attention' have shown how attentional deployment is affected by objects (for reviews see[78-80]). In particular, same-object advantages are usually considered to reflect object-based attention. For example, targets were detected faster at an invalidly cued same-object versus different-object location, despite identical distance between the cue and the target locations in both conditions[81]. Previous studies also demonstrated better performance when reporting multiple features of the same object compared to when these features belonged to separate objects (e.g.[82-85]). Same-object advantages have been suggested to reflect a facilitated, often automatic broadening of attention within but not between objects[86-89] (but see[90] for strategic control over the spreading of attention within objects), or within uniform versus non-uniform regions[91]. Similar to foveal vision, the difference in 'objecthood' between uniform and alternating trigrams may have modulated the attentional spreading of attention in the current study. The superior full-report performance for uniform compared to alternating (non-uniform) trigrams in Experiment 1 and 2 may thus well result from facilitated attentional spreading within uniform but not within alternating trigrams. When selecting a letter in a uniform trigram, automatic spreading of attention to the other same-contrast polarity letters may be beneficial in full report but detrimental in single-item report. Indeed, the automatic spreading of attention within objects has been shown to be deleterious when flankers were irrelevant (e.g.[92-94]). For instance, the categorization of a target letter was worse when incongruent distractor letters had the same color as the target compared to when both had a different color[92]. However, in the alternating trigrams, the attentional processing of all letters is not promoted, which should benefit single-item report but impair full report. Hence, the differential effect of stimulus uniformity between report types in Experiment 1 and 2 can be well explained by effects of unintentional spreading of attention.

The benefit of opposite- compared to same-contrast polarity flankers when reporting only the central item did not result in a similar advantage with full report. Instead, performance was worse for alternating compared to uniform trigrams when reporting all letters. Since low-level properties of uniform and alternating trigrams did not differ between report types, the absence of a polarity advantage in full report cannot be explained based on the stimulus' features alone, but rather suggests that interference also occurred at a higher level. Although still under debate[44], higher-level interactions in crowding have been suggested before, for instance, when target letter recognition was impaired more with letter flankers than with number flankers[42,43]. While these studies varied higher-order stimulus properties (e.g., categorical information), we varied task demands in the current study. Modulations of crowding by task demands were revealed earlier, with worse identification of a crowded target defined by form than by category[95] or different effects of target-flanker spacing in an identification compared to a magnitude comparison task[96]. In the current study, depending on the task demands, observers had to attend one or three items. As the size of the attentional window has been shown to be optimized in function of the task goal[97], the spatial deployment of attention likely varied between report types in the current study, with more focused attention in single-item report and more diffused attention in full report. Importantly, differences in the size of the attentional window have been shown to override key properties of crowding. Previously, inward-outward anisotropy was revealed under focused but not diffused attention19: An outward flanker was more deleterious than an inward flanker when the target appeared at the same eccentricity on each trial, but inward and outward flankers were equally deleterious when the target could appear at one of three possible eccentricities. Here, the locus of attention seems to have modulated another signature characteristic of crowding, namely the similarity rule. While our current results show strong attentional modulations of crowding, our main findings do not allow for strong claims regarding the overall role of attention in crowding.

In Experiment 3, identification of the single, central line was not better when flanking lines had opposite- compared to same-contrast polarity. Instead of the usual polarity advantage, our results revealed similar performance levels for uniform and alternating triplets when identification of only the single, central line was needed. Since opposite- compared to same-contrast polarity reduced crowding with more complex letters (Experiment 1 and 2) but not with simple lines (Experiment 3), this might suggest a role of stimulus complexity. However, the polarity advantage has been previously shown with stimuli of limited complexity, similar to our line stimuli. For example, discriminating the offset for a (vertical) vernier was superior with vertical flanking lines of opposite- compared to same-contrast polarity[34]. Instead of stimulus complexity, we propose that configural grouping between target and flanking lines might account for the absence of the polarity advantage when reporting the central line only. Recently, we showed better tilt discrimination for the central line within alternating compared to uniform triplets with bidirectional flankers (\/ or /\) but similar performance with unidirectional flankers (\\ or //)[53]. When examining the dependence of the polarity advantage on flanker tilt in a follow-up experiment, our findings revealed a larger configural superiority effect for uniform versus alternating triplets with unidirectional flankers, suggesting that emergent features benefitted performance for uniform triplets more than for alternating triplets. Taken together, the absence of the polarity advantage for triplets with unidirectional flankers in that study indicated that emergent features between same-contrast polarity lines benefitted performance to the extent that the performance level was similar as with opposite-contrast polarity flankers. In the current study, emergent features may explain the absence of the polarity advantage when reporting the central line tilt only as well. In particular, the configurations formed by two adjacent lines, either parallel (\\ or //) or mirrored (/\ or \/), may have provided task-relevant information to perform the line orientation task. Similar emergent features were associated with improved performance in a crowding task, and were shown to override conventional crowding rules[23,52]. For instance, when a diamond-like shape was better recognized when flanked by diamonds compared to Xs, a key role in this exception to the similarity rule was attributed to the emergent feature of closure[23]. In full report, accuracy for uniform lines possibly benefitted from strong task-relevant grouping, yet suffered from more severe crowding with same-contrast polarity lines. For alternating lines, reduced crowding by alternating contrast polarity was supposedly counteracted by weaker task-relevant grouping and costs of disrupting uni- formity (e.g.[32]). Hence, both with single-item and full report, the interplay between crowding and configural grouping may explain the similar performance for uniform and alternating lines. Importantly, our findings suggest—instead of the usual cost—an advantage of strong target-flanker grouping when providing a surplus in task-relevant information.

Our key results (Experiment 1 and 2) showed that stimulus uniformity was detrimental when attentional selection of only a single element was required, but beneficial when attention was broadened to all stimulus' elements. These findings suggested that the effect of similarity-based perceptual grouping is strongly dependent on how observers have to direct their attention in order to meet task demands. With stimuli of lesser complexity, Experiment 3 revealed neither the similarity rule in single-item report nor the inversion in full report. We attributed a crucial role in the divergent outcome with line triplets to the task-relevant information provided by configural grouping between adjacent lines. Taken together, our results provide further evidence for a strong association between attention and crowding. The reversal of the similarity rule found under broad attention puts strong constraints on the validity of basic crowding rules in real-life contexts. A well-established crowding rule, which was predominantly revealed when the recognition of a single object amongst task-irrelevant flankers was needed, was no longer valid when the task required the attentional selection of multiple items. We propose that even key properties of crowding are not rigid but are instead strongly dependent on the attentional demands imposed by the task.

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# Chapter 4:

# Multidimensional feature interactions in visual crowding: When configural cues eliminate the polarity advantage

**Abstract.** Crowding occurs when surrounding objects (flankers) impair target perception. A key property of crowding is the weaker interference when target and flankers strongly differ on a given dimension. For instance, identification of a target letter is usually superior with flankers of opposite versus same contrast polarity as the target (the 'polarity advantage'). High performance when target-flanker similarity is low has been attributed to the ungrouping of target and flankers. Here, we show that configural cues can override the usual advantage of low target-flanker similarity, and strong target- flanker grouping can reduce - instead of exacerbate - crowding. In Experiment 1, observers were presented with line triplets in the periphery and reported the tilt (left or right) of the central line. Target and flankers had the same (uniform condition) or opposite contrast polarity (alternating condition). Flanker configurations were either upright (||), unidirectionally tilted (\ \ or //), or bidirectionally tilted (\/ or /\). Upright flankers yielded stronger crowding than unidirectional flankers, and weaker crowding than bidirectional flankers. Importantly, our results revealed a clear interaction between contrast polarity and flanker configuration. Triplets with upright and bidirectional flankers, but not unidirectional flankers, showed the polarity advantage. In Experiment 2 and 3, we showed that emergent features and redundancy masking (i.e. the reduction of the number of perceived items in repeating configurations) made it easier to discriminate between uniform triplets when flanker tilts were unidirectional (but not when bidirectional). We propose that the spatial configurations of uniform triplets with unidirectional flankers provided sufficient task-relevant information to enable a similar performance as with alternating triplets: Strong-target flanker grouping alleviated crowding. We suggest that features which modulate crowding strength can interact non-additively, limiting the validity of typical crowding rules to contexts where only single, independent dimensions determine the effects of target-flanker similarity.

**Introduction.**

Context strongly modulates our perception of objects and their features. For instance, a letter presented in the periphery is usually harder to identify when surrounded by other letters than in isolation. This deleterious effect of surrounding clutter (flankers) on target perception is called crowding (e.g., Bouma, 1970; He et al., 1996; Pelli et al., 2004; Sayim & Wagemans, 2017; Strasburger et al., 1991; Stuart & Burian, 1962; Toet & Levi, 1992, for reviews see Herzog , 2015; Levi, 2008; Whitney & Levi, 2011). Crowding mainly manifests itself in peripheral vision (for foveal crowding, see Coates, Levi, Touch, &Sabesan, 2018; Malania, Herzog, & Westheimer, 2007; Sayim, Westheimer, & Herzog, 2008a, 2010, 2011), limiting various capacities, ranging from reading (Pelli et al., 2007; Pelli & Tillman, 2008), to visual search (Carrasco, Evert, Chang, & Katz, 1995; Reddy & VanRullen, 2007; Rosenholtz, Huang, Raj, Balas, & Ilie, 2012; Vlaskamp & Hooge, 2006), and object recognition (Levi, 2008; Pelli & Tillman, 2008; Whitney & Levi, 2011). Although crowding is usually assumed not to affect target detection (Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004), parts of targets or even entire targets are often lost in crowded displays (Coates, Bernard, & Chung, 2019; Sayim & Taylor, 2019; Sayim & Wagemans, 2017; Taylor & Sayim, 2020; Yildirim, Coates, & Sayim, 2019, 2020, 2021). A particularly strong loss was found in repeating patterns, for example, when observers report only two of three presented lines (Yildirim, Coates, & Sayim, 2020, 2021). This reduction of the number of perceived items is called redundancy masking (Sayim & Taylor, 2019), and has been suggested to contribute to the impaired recognition of crowded items (Yildirim, Coates, & Sayim, 2020).

Crowding has several key properties. Typically, crowding is stronger when flankers are located closer to the target (Bouma, 1970; Toet & Levi, 1992). Another signature characteristic of crowding is its dependence on target-flanker similarity. Target identification is generally better when the similarity between the target and its surrounding flankers is low. For instance, it was shown that identifying a crowded letter was superior with opposite compared to same contrast polarity flankers (Chung & Mansfield, 2009; Kooi et al., 1994; Rosen & Pelli, 2015; Rummens & Sayim, 2019, 2021), a benefit referred to as the 'polarity advantage' (Chakravarthi & Cavanagh, 2007). Similarly, previous studies revealed that flanker tilts closer to the target orientation yielded strongercrowding than flanker tilts further away (Andriessen & Bouma, 1976; Hariharan, Levi, & Klein, 2005; He, Wang, & Fang, 2019; Levi, Hariharan, & Klein, 2002; Solomon, Felisberti, & Morgan, 2004; Wilkinson, Wilson, &

Ellemberg, 1997). This ‘similarity rule’ of crowding has been shown for a broad range of other features such as binocular disparity (Astle, McGovern, & McGraw, 2014; Kooi et al., 1994; Sayim et al., 2008a), color (Kooi et al., 1994; Manassi et al., 2012; Põder, 2007; Sayim et al., 2008a; Greenwood & Parsons, 2020), motion (Greenwood & Parsons, 2020), and shape (Kooi et al., 1994; Nazir, 1992; Manassi etal., 2012; Sayim et al., 2010; but see Melnik, Coates, & Sayim, 2020).

The similarity rule suggests that crowding is always weaker when the closestflankers strongly differ from the target on a given dimension. However, purely local interactions between the target and the innermost flankers do not reliably predict crowding. Instead, performance depends on the whole configuration, and, more specifically, on how strongly a target groups with its global context (the target and all its flankers) (e.g., Doerig et al., 2019; Herzog & Manassi, 2015; Choung, Bornet, Doerig, & Herzog, 2021; Sayim, Westheimer, & Herzog, 2010, 2011). For example, offset discrimination for a black vernier was worse when embedded in an array of alternating black and white flanking lines compared to when all flanking lines were white (Sayim, Westheimer, & Herzog, 2008a). The innermost flankers were white in both conditions, hence, not the local but the global target context accounted for the different results. In general, to adequately predict performance in crowding tasks, local target-flanker similarity is not sufficient, but how strongly the target groups with the global context needs to be taken into account. Several measures have been proposed to quantify target- flanker grouping. When observers rated how much the target stood out from its flankers, higher target conspicuity was associated with weaker crowding (Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim & Cavanagh, 2013). Similarly, performance in a visual search task was predictive of crowding: targets that ‘popped out’ in visual search were less crowded (Sayim, Westheimer, & Herzog, 2011; Gheri, Morgan, & Solomon, 2007). Moreover, contextual modulation itself was proposed as a measure of grouping strength, with performance in a crowding task quantifying the strength of (target-flanker) grouping (Sayim, Westheimer, & Herzog, 2010). In general, it was shown that when target-flanker grouping was weak, the target stood out from its context, resulting in better performance than when grouping was strong (Banks, Larson, & Prinzmetal, 1979; Livne & Sagi, 2007, 2010; Malania, Herzog, & Westheimer, 2007; Manassi, Sayim, & Herzog, 2012; Rosen & Pelli, 2015; Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim, Westheimer, & Herzog, 2010, 2011).

Conventional crowding rules of spacing, similarity, and grouping have typically been shown using task-irrelevant flankers: observers were asked to report a single target, while processing of the flankers was not required. However, when the context was task-relevant, previous studies showed that conventional crowding rules did not readily apply (Melnik, Coates, & Sayim, 2018; Rummens & Sayim, 2021). For instance, when all letters of a trigram had to be reported, the recognition of the central letter was only minimally better (Chung & Mansfield, 2009) or similar (Rummens & Sayim, 2021) when neighboring letters had opposite compared to identical contrast polarity. These findings are consistent with high target-flanker similarity being less costly when all letters were targets instead of the central letter only (Huckauf & Heller, 2002; Rummens & Sayim, 2021; Zhang, Zhang, Liu, & Yu, 2012). Furthermore, word recognition, a task in which all letters are task-relevant, has been shown to benefit from strong (compared to weak) grouping between adjacent word parts. Specifically, performance was better for words consisting of parts with same compared to opposite polarity, revealing benefits of uniformity when multiple crowded items were task-relevant (Rummens & Sayim, 2019). Conventional crowding rules were also called into question when target and flankers combined into a configuration with particular emergent features. For example, when stimuli comprised a central target chevron (pointing up or down) flanked by chevrons on all four sides, crowding was surprisingly weaker at closer than at larger spacings between the target and a flanking chevron (Melnik, Coates, & Sayim, 2018). This reversal of the typical effect of target-flankerspacing was attributed to emergent features of the target and the (critical) flanker. The effect of strong grouping yielding weak crowding was increased when observers reported the entire target-flanker configuration (making the critical flanker task-relevant). In a subsequent study, a diamond shape was better recognized amongst diamonds versus Xs, again showing a reversal of the similarity rule (Melnik, Coates, & Sayim, 2020). These findings suggested that strong grouping of the target with the flankers can - contrary tothe generally deleterious effect - alleviate crowding. Taken together, when flankers were task-relevant or informative about target identity by forming a salient configuration with the target, key properties of crowding did no longer apply.

Effects of target-flanker similarity and grouping have typically been investigated by varying similarity on a single feature dimension, while controlling for target-flanker differences on other dimensions. For instance, studies that revealed the polarity advantage with a rotated T-task typically compared performance between stimuli comprising Ts of same versus opposite contrast polarity (e.g., Chakravarthi & Pelli, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Rummens & Sayim, 2021). As all items were Ts, potential effects of shape differences between target and flankers were minimized. When target and flankers did vary on several dimensions (color, spatial frequency, orientation), multiple features interacted in an additive fashion: performance improved with increasing number of feature dimensions on which the target differed from its flankers (Põder & Wagemans, 2007). Similarly, while temporal (i.e., flanker preview; Huckauf & Heller,2004; Scolari, Kohnen, Barton, & Awh, 2007) and figural ungrouping (Sayim, Westheimer, &Herzog, 2010; Manassi, Sayim, & Herzog, 2013) have been shown to individually reduce – but usually not abolish – crowding, crowding was absent when both types of ungrouping were combined (Sayim, Westheimer, & Herzog, 2008b). Additive effects of features in multiple dimensions were also suggested with foveal studies, revealing that the combined effect of grouping by proximity and (luminance) similarity (Kubovy & van den Berg, 2008)or proximity and collinearity (Claessens & Wagemans, 2005) was equal to the sum of both individual effects.

By contrast, recent crowding studies suggested that multiple features may also interact in a non-additive manner. For instance, as outlined above, whether close target-flanker spacing hindered or helped performance depended on the emergent feature elicited by the combination of the target and flankers (Melnik, Coates, & Sayim, 2018). Similarly, configural cues have been suggested to counteract the typical benefit for target identification when flankers were of opposite compared to same contrast polarity as the target (Rummens & Sayim, 2021, Experiment 3). In the latter study, observers were instructed to report the tilt of the central line (left or right) of three horizontally arranged lines (i.e., triplets), with each line having a left- or rightward tilt (8 possible configurations; see Fig. 1A for an example). Interestingly, both with 100 ms and 150 ms presentation duration, there was no polarity advantage: Identification of the central line tilt was similar when target and flankers had the same contrast polarity (uniform condition) compared to the opposite contrast polarity (alternating condition) (see Fig. 1B). Similar performance in the uniform and alternating conditions suggested that uniform triplets benefitted from configural cues not available in alternating triplets. Hence, the validity of the similarity rule seemed contingent on orientation cues of the stimulus. The lack of an advantage for alternating compared to uniform triplets contrasted with earlier studies showing a polarity advantage with similar stimuli (e.g., a vernier flanked by same or opposite contrast polarity lines; Sayim, Westheimer, & Herzog, 2008a).

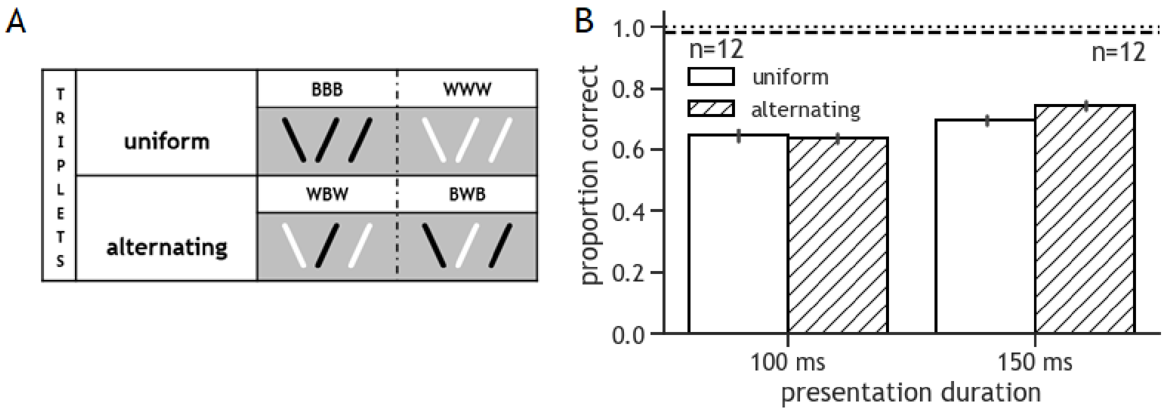


**Fig.1.** (A) Examples of stimuli as used in Rummens & Sayim (2021). Stimuli consisted of three tilted lines that were either uniform or alternating in contrast polarity. Uniform triplets were all white ('WWW') or all black ('BBB'), alternating triplets consisted of a black central line with whiteflanking lines ('BWB'), or vice versa ('WBW'). Each line was either tilted to the left or right from vertical, resulting in 8 possible configurations. (B) In two experiments (100 and 150 ms presentation duration; 12 participants each), the polarity advantage was absent when reporting the tilt of the central line. Error bars represent the standard error of the mean. The dotted (dashed) line denotes unflanked performance for 100 (150) ms. Adapted from Rummens & Sayim (2021).

In the current study, we examined how the interaction of multiple features – contrast polarity and orientation – conjointly affected crowding. Specifically, we examined whether - and how - flanker orientations affected the polarity advantage in crowding. To this aim, we measured tilt discrimination of a crowded line (Experiment 1). Stimuli comprised three horizontally arranged lines (line triplets). Observers were asked to report the tilt of the central line (either left- or rightward). The orientations of the flanking lines were varied: upright (||), unidirectionally tilted (\ \ and //), or bidirectionally tilted (\/ and /\). In two conditions, the flankers had either the same contrast polarity as the target (uniform condition), or the opposite contrast polarity (alternating condition). Within each block, contrast polarity and flanker tilt were kept constant, and only the central line tilt was randomized (left or right). Bidirectional flankers yielded stronger crowding and unidirectional flankers weaker crowding than upright flankers. The polarity advantage was observed with upright and bidirectional but not unidirectional flankers, demonstrating a clear interaction between contrast polarity and orientation.

In two follow-up experiments, we investigated to what extent the two factors 'emergent features' (Experiment 2) and 'redundancy masking' (Experiment 3) contributed to the absence of the polarity advantage with unidirectional flankers. In Experiment 2, observers performed an odd quadrant task, indicating which line triplet differed from the other three triplets presented. As in Experiment 1, line triplets had unidirectional or bidirectional flankers (no upright flankers), and were uniform or alternating in contrast polarity. The odd line triplet differed from the other three triplets by the central line tilt only. Our results revealed better discrimination between triplets with unidirectional flankers (e.g., \ \ \ versus \/\) compared to bidirectional flankers (e.g., \ \/ versus \//). Specifically, a configural superiority effect was found for triplets with unidirectionalflankers, as observers were faster to report the odd-one-out with triplets than with single lines. Triplets with bidirectional flankers did not show a configural superiority effect.Taken together, our findings suggested that emergent features benefitted performance for line triplets with unidirectional flankers only. Importantly, the benefit of emergent features was greater when discriminating between uniform than between alternatingtriplets with unidirectional flankers.

In Experiment 3, we investigated whether redundancy masking contributed to the good performance with uniform triplets flanked by unidirectional lines in Experiment 1. As redundancy masking most strongly affects highly regular stimuli (Yildirim, Coates, & Sayim, 2020), it is likely that it affected triplets comprised of three similarly tilted lines (\ \ \- or ///-triplets) but not when the central line was of opposite tilt than both its flankers (\/\-or /\/-triplets). A reduction of the perceived number of identical lines may have provided task-relevant information that facilitated the discrimination of uniform triplets with unidirectional flankers. In Experiment 3, observers reported the number of lines of stimuli comprising three to five tilted black lines. Critically, uniform triplets with uni- and bidirectional flankers, identical to those of Experiment 1, were included. Our findings revealed a reduction of the number of reported lines when all lines were tilted in the samedirection (e.g., \ \ \) but not when triplets contained opposite tilt directions (e.g., \/\). These findings suggested that redundancy masking – similarly to emergent features – benefitted the discrimination between \ \ \- and \/\-triplets but not between \ \/- and \//- triplets.

In sum, we showed that the often-replicated polarity advantage was absent when triplets had flankers with unidirectional tilts. We propose that spatial characteristics of the stimulus - emergent features (Experiment 2) and the susceptibility to redundancy masking (Experiment 3) – likely provided observers with cues that contributed to the good performance with uniform triplets comprising unidirectional flankers (Experiment 1). Spatial configurations formed by only three lines may contain sufficiently potent cues to overcome the usual cost of same versus opposite contrast polarity.

**Experiment 1: tilt discrimination task.**

**Method.**

*Subjects.*

Eight observers (M = 3, F = 5; age range: 21 – 28 yrs) with self-reported normal or corrected-to-normal vision participated. Prior to the experiment, all participants provided their written informed consent. Experiments were in accordance with the ethical standardsof the Declaration of Helsinki, and approved by the Ethics Committee of the University of Bern.

*Apparatus.*

A custom-written Python program was run by Psychopy2 (Peirce, 2019) on a PC computer. Stimuli were displayed on a 22 inch CRT monitor (HP, p1230, refresh rate = 110 Hz, resolution = 1152 x 864). Supported by a head- and chinrest, observers were seated at 57 cm distance from the screen in a dimly lit room.

*Stimuli.*

Stimuli (see Fig. 1A) were line triplets comprising three adjacent lines, each of 1° height and .07° width. Lines were .75° apart, horizontally arranged, and centered on the horizontal meridian. Line triples were centered at 10° eccentricity, and randomly shown in the left or right hemifield. The tilt of the central target line was varied with an adaptive QUEST-procedure (Watson & Pelli, 1983), with a random clockwise or counterclockwise tilt of 15° from vertical as starting value. There were three types of flanker configurations: flanking lines were either vertical (*upright* flankers: ||), were both tilted to the left or right (*unidirectional* flankers: \ \ or //), or had one leftward and one rightward tilt (*bidirectional* flankers: \/ or /\). When tilted, flanker orientations comprised all possible combinations of 10° or 20° counterclockwise or clockwise tilts from vertical. Uni- and bidirectional flankers were *symmetrical* when identical in absolute value, or *non- symmetrical* when absolute values of the left and right flanker differed. Overall, seventeenflanker configurations (one upright, eight unidirectional, and eight bidirectional flanker configurations), and a no-flanker condition were included. Lines were either *uniform* or *alternating* in contrast polarity. Uniform stimuli consisted of all black (.02 cd/m$^2$; 'BBB')or all white (89.9 cd/m$^2$; 'WWW') lines. Alternating stimuli consisted of a black central line with white outer lines ('WBW'), or vice versa ('BWB'). Line triplets were displayed ona middle grey background (45.0 cd/m$^2$).

*Procedure.*

We measured orientation discrimination for the central line within a line triplet. Line triplets varied in contrast polarity and flanker configurations. Neighboring lines were of the same contrast polarity in uniform triplets, and of opposite contrast polarity in alternating triplets. Both for uniform and for alternating triplets, we measured tilt discrimination for the central line when surrounded by the different flanker configurations introduced above.

The experiment comprised two sessions of approximately 75 minutes each, which were separated by a 30 minutes break. At the beginning of each session, we measured performance for unflanked black or white lines. In each session, observers completed all flanker configurations for two contrast polarity conditions. Trials were blocked by contrast polarity and flanker configuration. Each block consisted of 50 trials, preceded by four practice trials that were not part of the QUEST-staircase. The contrast polarity condition switched after every block. The order of contrast polarity conditions and the order of flanker configurations for each contrast polarity condition were randomized. Eachparticipant completed 3600 trials (3500 flanked; 100 unflanked) in total.

*Task.*

Observers were asked to judge the tilt direction, either left- or rightward relativeto the vertical, of the central line within a line triplet. The experimental procedure is depicted in Fig. 2B. First, a black fixation dot was presented in the center of the screen. Participants were instructed to focus on the fixation dot throughout each trial. Upon key press, a triplet was presented for 150 ms at 10 degrees eccentricity randomly to the left orright of the fixation dot. After stimulus presentation, the fixation dot remained on the screen for 50 ms. Next, a question mark was presented until observers pressed 's' for a leftward or 'k' for a rightward tilt.

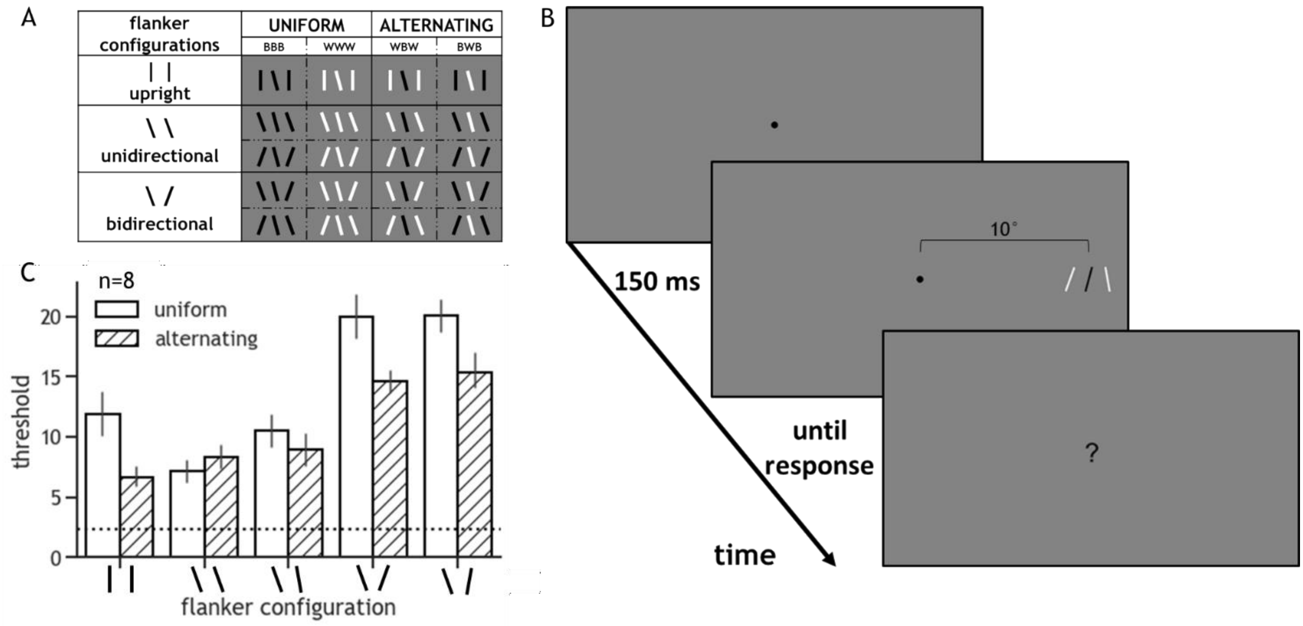


**Fig. 2. Overview of the stimuli (A), procedure (B), and results (C).** (A) Stimuli were line triplets, either uniform or alternating in contrast polarity. Uniform triplets consisted of all black (BBB) or all white (WWW) lines. Alternating triplets comprised a black central line with white flankers (WBW) or vice versa (BWB).Flanker tilts were either upright (||), unidirectional (\ \ or //), or bidirectional (\/ or /\). Upright flankers had no tilt, uni- and bidirectional flankers had tilts of -20°, -10°, 10°, or 20°. Uni- and bidirectional flanker tilts were either symmetrical (same absolute values) or asymmetrical (different absolute values). (Only symmetrical configurations with tilts of 20° in absolute value are depicted.) (B) Time course of a trial, showing an alternating triplet with non-symmetrical bidirectional flankers. (C) Results of the tilt discrimination experiment. Thresholds are displayed as a function of flanker configurations, separately for uniform and alternating triplets. Error bars indicate the standard error of the mean. The dotted line denotes the 75 percentcorrect threshold of the unflanked condition. With uniform and alternating triplets combined, performance was superior with unidirectional compared to upright and bidirectional flankers. Triplets with upright and bidirectional flankers showed the polarity advantage, with better performance with alternating compared to uniform triplets.

## Results.

Per participant, we obtained the 75 percent correct thresholds for each conditionof contrast polarity by flanker configuration. Thresholds for uniform BBB- and WWW- triplets were averaged as well as for alternating WBW- and BWB-triplets. Results are displayed in Fig. 1C. We conducted a repeated measures ANOVA including the thresholds asdependent variable, and both contrast polarity (uniform and alternating) and flanker configurations (upright, and both the symmetrical and non-symmetrical variants of unidirectional and bidirectional flanker configurations) as factors. All post-hoc pairwise comparisons were Tukey-tests.

We found a main effect of contrast polarity. All flanker configurations taken together, tilt discrimination for the central line was better for alternating compared to uniform line triplets (F(1,7)=45.80, p<.001, $\eta^2$=.07). A main effect of flanker configuration (F(4,28)=29.13, p<.001, $\eta^2$=.50) was characterized by worse performance for bidirectional flanker tilts (symmetrical and asymmetrical) compared to both unidirectional (symmetrical and asymmetrical) and upright flankers (p-values for all six comparisons: <.001). Performances of the upright, symmetrical unidirectional, and asymmetrical unidirectional flankers did not differ (all p*s*>.52), neither did performances of symmetrical and asymmetrical bidirectional flankers (p>.99). The effect of contrast polarity depended on flanker configurations (F(4,28)=4.15, p<.001, $\eta^2$=.05). Performance for alternating compared to uniform line triplets was superior for upright (p<.02) and bidirectional flankers (symmetrical: p=.01; asymmetrical: p<.04), but similar for unidirectional flankers (symmetrical: p=1.0; asymmetrical: p=.98).

Next, we examined whether the magnitude of flanker tilts in the uni- and bidirectional flankers condition affected thresholds (see Fig. 3). Uni- and bidirectional flanker configurations had absolute average deviations from the vertical of 10, 15, and 20 degrees. Absolute tilts averaged to 10 and 20 degrees when symmetrical, and to 15 degrees when asymmetrical. For example, asymmetrical bidirectional flankers with one flanker tilted by 10 degrees to the left and the other by 20 degrees to the right have an average absolute tilt of 15 degrees. To test for any differences in threshold depending on tilt magnitude of the flankers, we ran a repeated measures ANOVA with flanker configuration (uni- and bidirectional tilts), absolute deviation from vertical (10°, 15°, and 20°), and contrast polarity (uniform and alternating) as factors, and thresholds as dependent variable. A main effect of deviation from vertical (F(2,14)=6.94, p<.01, $\eta^2$=.02) indicated better performance with 10 degree tilts compared to both other tilts (10° vs 15°:p<.05; 10° vs 20°: p<.05). Thresholds were lower for alternating compared to uniform triplets (F(1,7)=17.70, p<.01, $\square^2$=.04), and for uni- relative to bidirectional tilts (F(1,7)=46.84, p<.001, $\square^2$=.51). As shown in our first analysis, the effect of contrast polarity depended on flanker configuration (F(1,7)=16.81, p<.01, $\square^2$=.05). Furthermore, we found a three-way interaction between flanker configuration, average flanker tilt, and contrast polarity (F(2,14)=5.07, p<.05, $\square^2$=.02).

With unidirectional flankers, the flankers' absolute deviation from vertical affected thresholds neither for uniform (p-values of all three comparisons above .19) nor foralternating triplets (p-values of all three comparisons above .99). With bidirectional flankers, we found a linear increase in thresholds with increasing average tilt for uniform bidirectional triplets (10° vs 20°: p<.01) but no difference between tilts for its alternating counterparts (10° vs 20°: p=1.0).

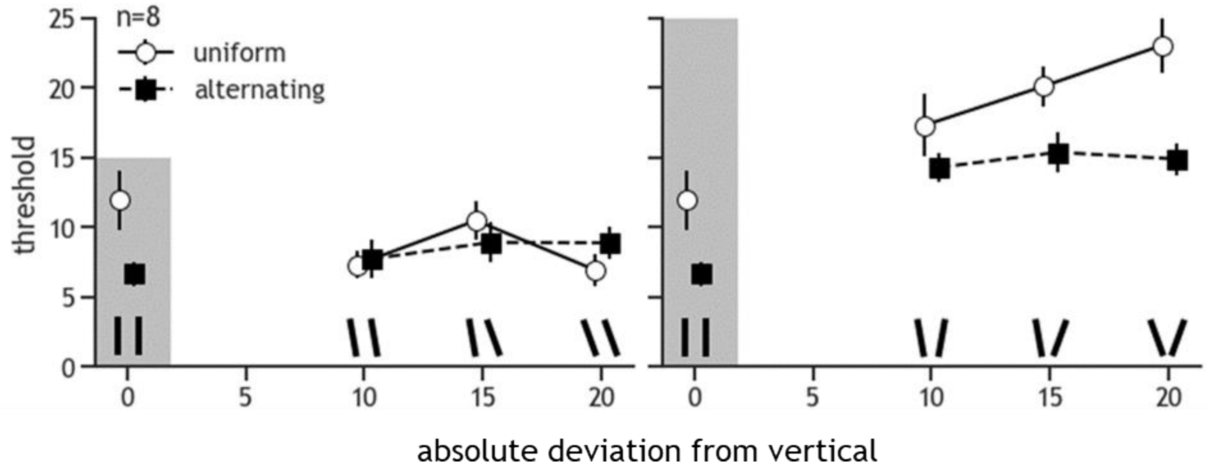


**Fig. 3.** Thresholds plotted as a function of the flankers' average absolute deviation from vertical (in degrees), separately for uniform (left graph) and alternating (right graph) triplets. Thresholds for unidirectional and bidirectional flankers are shown in the left and right graph, respectively. Both graphs show the thresholds of upright flankers (0° average tilt) on a grey background. With unidirectional flankers, thresholds for neither uniform nor alternating triplets were affected by the flankers' absolute deviation from the vertical. With bidirectional flankers, the polarity advantage increased with larger absolute deviations from vertical.

**Discussion.**

The findings of Experiment 1 revealed that the effect of contrast polarity strongly depended on the flanker configuration. When flankers were upright or bidirectional, the typical polarity advantage was found, with superior tilt discrimination in alternating compared to uniform triplets. Surprisingly, there was no polarity advantage when flankers were unidirectional, with no difference in performance between uniformand alternating triplets. In fact, with unidirectional flankers, the polarity advantage was absent for all average absolute flanker deviations from the vertical (10, 15, and 20 degrees). Interestingly, with bidirectional flankers, there was a clear polarity advantage, which increased linearly with larger absolute deviation of the flankers from the vertical.

Despite good overall performance for uniform triplets with unidirectional flankers, the absence of the polarity advantage with unidirectional flankers cannot be explained by ceiling performance. The thresholds for uniform triplets with unidirectional flankers (both for asymmetrical and symmetrical) are above 2.5 times the single line performance, leaving plenty of margin for improvement. Instead, we propose that the spatial configuration formed by the central line and both flankers played a key role for theabsence of the polarity advantage with unidirectional flankers. Importantly, since flanker tilts and contrast polarity did not vary within a block, one out of two possible triplets was presented on each trial. Therefore, if performance for one of the triplets within a block benefitted from a salient configural cue, performance for the other triplet could similarly benefit from the absence of such a cue. Specifically, we hypothesized that observers could use configural cues that facilitated discriminating between uniform triplets with unidirectional flankers (\ \ \ versus \/\ and /// versus /\/) but not (or to a lesser extent) between uniform triplets with bidirectional flankers (\ \/ versus \// and //\ versus /\ \). If so, the advantage of configural cues for uniform triplets with unidirectional flankers may have enabled similar performance as with alternating triplets. The presence of the polarityadvantage with bidirectional flankers seems to indicate that performance for uniform triplets with bidirectional flankers could not - or only minimally - benefit from configural cues, resulting in the typical worse performance for uniform compared to alternating stimuli.

**Experiment 2: Odd quadrant task.**

In Experiment 2, we used an odd quadrant task (e.g., Pomerantz, Sager, & Stoever, 1977) to examine whether emergent features facilitated discriminating between uniform triplets with unidirectional (\ \ \ versus \/\ and /// versus /\/) but not with bidirectional flankers (\\/ versus \// and /\\ versus //\).

**Method.**

*Subjects.*

Ten new observers (9 female, 1 male) between 19 and 47 year old participated for course credit. All subjects had normal or corrected-to-normal vision, and provided informed consent prior to the experiment.

*Apparatus.*

Apparatus was identical to Experiment 1.

*Stimuli.*

Stimuli consisted of four simultaneously presented line triplets, each centered in a six-by-six degrees quadrant. Quadrants were arranged in a two-by-two matrix. A line triplet appeared 4.24° away from the screen center (see Fig. 4A for an example). Line triplets were identical to those of Experiment 1: three horizontally arranged, near-vertical lines of 1° height and .07° width were separated by a spacing of .75°. The tilt of the central line was 15° clockwise or counterclockwise from vertical, and - different from Experiment 1 - only absolute flanker tilts of 20° but not 10° were included. Uniformtriplets consisted of all black (BBB-triplets) or white lines (WWW-triplets), alternating triplets had a black central line with white flankers (WBW-triplets) or the other wayaround (BWB-triplets). Luminance values of black (.02 cd/m$^2$), white (45.0 cd/m$^2$), and grey (89.9 cd/m$^2$) were the same as in Experiment 1. Four flanker configurations were included: \ \ and // had unidirectional tilts, and \/ and /\ had bidirectional tilts. Each stimulus consisted of three quadrants with identical line triplets, and of one 'odd quadrant' containing a triplet differing from the other triplets by the central line tilt only. In the baseline condition, each quadrant contained a single tilted line, with one line of opposite tilt compared to the three other lines. Single lines were either all black or all white. The location of the odd quadrant was randomized.

*Procedure.*

Observers were instructed to indicate the line triplet (or single line in the baseline condition) that differed from the others as fast and accurate as possible. Every trial began with a fixation dot presented in the center of the screen. When pressing spacebar, the stimulus was presented until response, and the fixation dot was replaced by the mouse pointer. Participants responded by clicking one of the four triplets with the mouse. The experimental procedure is shown in Fig. 4A.

Trials were blocked in identical fashion to Experiment 1, i.e., by flanker configuration (\ \, / /, \/, and /\) and contrast polarity (WWW, BBB, BWB, and WBW), resulting in 16 different conditions. Additionally, observers completed two baseline conditions, one with single black lines and one with single white lines. All conditions were performed in randomized order. Overall, 18 blocks of 50 trials (900 trials) were completed.We registered accuracy (correct or incorrect) and reaction time, i.e. the time between stimulus onset and response.

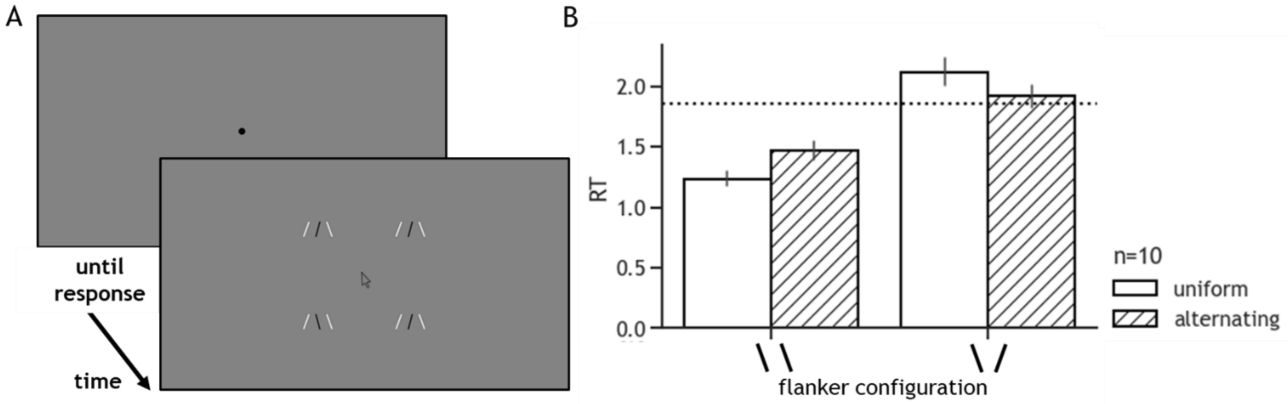


**Fig. 4. Procedure (A) and results (B) of the odd quadrant task in Experiment 2.** (A) Each trial of the odd quadrant task started with a central fixation dot. Upon key press, four line triplets were presented in a two-by-two configuration. One of the four triplets was unique, and observers were instructed to click the 'odd' triplet as fast and accurate as possible with the mouse. (B) Separately for uniform and alternating triplets, correct RT was plotted as a function of flanker tilt, with unidirectional flankers on the left (\ \ and / /) and bidirectional flankers on the right (\/ and /\). The dotted line shows the performance for unflanked lines (black and white combined). Performance below the dotted line indicates configural superiority. Error bars indicate the standard error of the mean. Better performance for triplets with unidirectional tilts compared to single lines indicated a configural superiority effect. There was no configural superiority for triplets with bidirectional flankers. The effect of contrast polarity depended on flanker configuration: RTs for uniform compared to alternating triplets were faster with unidirectional flankers, but slower with bidirectional flankers.

**Results.**

Results for BBB- and WWW-triplets were combined (uniform condition), as well as those for WBW- and BWB-triplets (alternating condition). After the removal of incorrect responses (1.9 percent of all trials), trials with RTs of more than two standard deviations below or above the individual mean were excluded. If subtracting two standard deviations from the individual mean had an outcome below 100 ms, 100 ms was used as a cutoff as such fast RTs would not reflect the process of interest (Luce, 1986). Overall, 3.9 percentof the accurate trials were excluded. We performed a repeated-measures ANOVA with reaction time (RT) as dependent variable, and contrast polarity (uniform or alternating) and flanker configuration (unidirectional or bidirectional) as factors. All post-hoc pairwise comparisons were Tukey-tests.

We found a main effect of flanker configuration ($F(1,9)=120.98$, $p<.001$, $\eta^2=.81$):RTs were faster for triplets with unidirectional compared to bidirectional tilts, and Tukey- tests revealed this unidirectional advantage both for uniform ($p<.001$) and alternating ($p<.001$) triplets. Furthermore, the interaction between flanker configuration and contrast polarity ($F(1,9)=24.09$, $p<.001$, $\eta^2=.08$) was characterized by better performance for uniform compared to alternating triplets with unidirectional flankers ($p<.01$), and worseperformance with bidirectional flankers ($p=.01$).

**Discussion.**

The findings of the odd quadrant task demonstrated that, regardless of stimulus uniformity, discriminating between triplets when flankers were unidirectional was superior than when bidirectional. Triplets with unidirectional flankers showed a clear configural superiority effect: Compared to performance with single lines, discrimination was markedly enhanced when unidirectional flankers were added. In particular, the better discrimination between triplets with unidirectional flankers (e.g., \ \ \ versus \/\) comparedto without flankers suggested that performance could benefit from emergent features: the absence versus the presence of all parallel lines was rather easy to detect. As performancewas not better with bidirectional flankers than without flankers, there was no configural superiority for triplets with bidirectional flankers. Similar performance for triplets with bidirectional flankers versus single lines suggested that the addition of flanking lines didnot elicit configural cues that facilitated discrimination. In fact, all triplets with bidirectional flankers (\ \/ & \//; //\ & /\ \) were similarly characterized by the emergent features of parallelism and mirror symmetry (Stupina, 2010), which may explain why these configural cues were not particularly helpful for their discrimination. Taken together, emergent features seem to have benefitted performance for triplets with unidirectional flankers but not bidirectional flankers.

Furthermore, the effect of contrast polarity was dependent on flanker configuration. Triplets with unidirectional flankers showed a clear configural superiority effect, with worse performance for alternating compared to uniform triplets. The smaller configural superiority effect for alternating compared to uniform triplets suggested that the advantage of emergent features weakened when lines alternated in contrast polarity. With bidirectional flankers, where performance did not benefit from emergent features, performance was worse with uniform compared to alternating triplets. Hence, flanking lines of opposite contrast compared to same contrast polarity benefitted performance in the absence of emergent features (bidirectional flankers), but deteriorated performance inthe presence of emergent features (unidirectional flankers).

The results of the odd quadrant task showed a clear configural superiority effect for triplets with unidirectional flankers but not with bidirectional flankers. Importantly, when flankers were unidirectional, the configural superiority effect was greater for uniform compared to alternating triplets. The larger benefit of emergent features when unidirectional flankers had the same compared to the opposite contrast polarity as the target may well play a role in the absence of the polarity advantage with identical stimuli in Experiment 1. Specifically, the greater advantage of emergent features in uniform compared to alternating triplets revealed in Experiment 2 seems to have overcome the usual stronger crowding cost of same versus opposite contrast polarity flankers, revealing similar performance for uniform and alternating triplets with unidirectional flankers. With bidirectional flankers, there was no configural superiority effect, suggesting that observers did not benefit from any configural cues. Performance was better with alternating compared to uniform triplets with bidirectional flankers, similar to the polarity advantage revealed with identical stimuli in Experiment 1.

**Experiment 3: enumeration task.**

In Experiment 3, we investigated whether redundancy masking (Sayim & Taylor, 2019; Yildirim, Coates, & Sayim, 2020) may have contributed to the good performance for uniform triplets with unidirectional flankers in Experiment 1. Since redundancy masking is usually stronger with highly regular stimuli (Yildirim, Coates, & Sayim, 2020), we predictedthat a reduction in the number of perceived lines would mainly occur for highly regular \ \ \- and ///-triplets, but not for the less regular \/\- and /\/-triplets. Therefore, redundancy masking might have improved the discrimination between triplets of three similarly tilted lines and triplets with the central line of opposite tilt to both its flankers. By contrast, given the low regularity of triplets with bidirectional flankers, redundancy masking should not differentially affect their enumeration. Thus, we did not expect redundancy masking to improve the differentiation between triplets with bidirectional flankers. To probe our hypothesis, observers were presented with three to five tilted black lines and asked to report the number of lines.

**Method.**

*Subjects.*

All ten observers of Experiment 2 participated in Experiment 3.

*Apparatus.*

Apparatus was identical to Experiment 1 and 2.

*Stimuli.*

Stimuli consisted of three to five near-vertical black lines that were horizontally arranged. Triplets were identical to those of Experiment 1, comprising tilted lines each of 1° height and .07° width. The spacing between lines was .75°. The left- or rightward tilt was again 15 degrees for the central line and 20 degrees for the flanking lines, resulting in eight possible line configurations: four configurations had unidirectional flanking lines (\\\, ///, \/\, /\/) and four had bidirectional flanking lines (\//, \ \/, /\ \, //\). The central line of a line triplet was centered at 10 degrees eccentricity, and presented in either the leftor right visual field. Four-line stimuli were generated by randomly adding a line on the left or right side of a triplet, and five-line stimuli had an additional line on both sides of a triplet. The tilt(s) of the additional line(s) of four- and five- line stimuli were randomly chosen from the tilts of the triplet's outer lines (without replacement). All stimuli thus hadone of the eight triplets at its core (i.e., 'core triplets'), to which zero, one, or two tilted lines were added. Given the study objective, we were only interested in the performance with regard to the three-line stimuli. Four- and five-line stimuli were only included as fillers to obtain a certain variance in the correct number response.

*Procedure.*

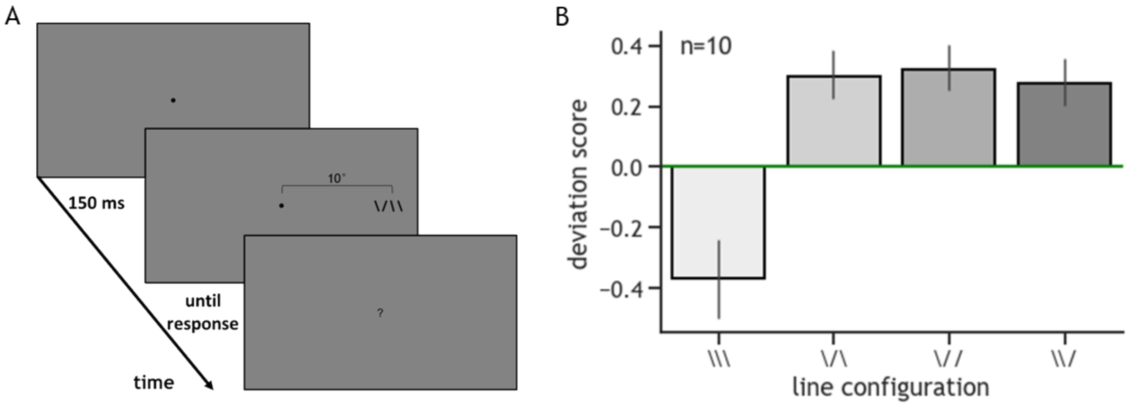


**Fig. 5. Procedure (A) and results (B) of the enumeration task in Experiment 3.** (A) Each trial began with a central fixation dot. Upon key press, a three-, four-, or five-line stimulus was presented for 150 ms in the left or right visual field. Following the stimulus presentation, observers responded with a number between zero and nine. (B) Deviation scores of triplets – calculated as the number of lines presented subtracted from the number of lines reported - are shown for each line configuration. Four- and five-line stimuli were shown as fillers and thus discarded. Scores were combined for equivalent triplets (\ \ \ & ///; \/\ & /\/; \// & /\ \; \ \/ & //\). A deviation score of below zero (below the green line) indicates reporting less than the number of lines presented ('underreporting'), and a deviation score larger than zero (above the green line) means reporting more than the number of presented lines ('overreporting'). On average, \ \ \- and ///-triplets were underreported, suggesting that these triplets were affected by redundancy masking. All other triplets were overreported, showing no redundancy masking.

The procedure of the enumeration task is shown in Fig. 5A. The task was to report the number of presented lines. Observers were instructed to focus on the fixation dot inthe center of the screen. When pressing spacebar, a line stimulus was presented for 150 ms, randomly in the left or right hemifield. After stimulus presentation, a question mark replaced the fixation dot, indicating that a response between zero and nine needed to be given with the numberpad.

Stimuli varied in the number of lines and their core triplet. Trials were blocked by the tilt of the core triplets' outer lines (unidirectional or bidirectional). Half of the observers started with a unidirectional block, the other half with a bidirectional block. Blocks alternated between uni- and bidirectional. Each block consisted of 120 trials, with thirty trials - equally divided between three-, four- and five-line stimuli - for each of the four core triplets. Within each block, trials were presented in random order. Observers performed 8 blocks or 960 trials (320 test and 640 filler trials) in total.

**Results.**

Our aim was to investigate whether redundancy masking contributed to the discriminability of uniform triplets with unidirectional outer lines (\ \ \ & /// versus \/\ &

/\/), but not between triplets with bidirectional outer lines (\ \/ & //\ versus \// & /\ \). We calculated the average deviation scores for triplets, subtracting the number of lines presented from the number of lines perceived. The deviation scores for equivalent triplets (\ \ \ & ///; \/\ & /\/; \ \/ & //\; \// & /\ \) were combined. Deviation scores below zero indicated 'underreporting', with observers reporting less than the number of presented lines. Deviation scores above zero indicated 'overreporting', with observers reporting morethan the number of presented lines.

A repeated measures ANOVA with deviation scores as dependent variable revealed amain effect of line configuration ($F(3,27)=26.98$, $p<.001$, $\eta^2=.75$), the only factor included in the model. Tukey-tests revealed different deviation scores for \ \ \- and ///-triplets (negative deviation scores) compared to \/\- and /\/-triplets (positive deviation scores; p<.001), and no difference between \ \/- and //\-triplets versus \//- and /\ \-triplets (both positive deviation scores; p=.60) (see Fig. 5B).

**Discussion.**

Our results showed that the number of perceived lines strongly depended on the tiltof the triplets' constituting lines. Redundancy masking – as indicated by deviation scores below zero - occurred for \ \ \-triplets but not for \/\-triplets. On average, triplets of three similarly tilted lines were underreported, whereas triplets with a central line of opposite tilt to its flanking lines were overreported. Redundancy masking did not occur for triplets with bidirectional flankers, as the reported number of lines was larger than the presented number of lines for both \//- and \\/-triplets.

Enumeration errors thus differed between \ \ \- and \/\-triplets: While \ \ \-triplets were underreported, \/\-triplets were overreported. Such differences in enumeration errors – and thus in the perceived number of lines - may have been beneficial when discriminating between triplets with unidirectional flankers. Although the task of Experiment 1 required reporting the tilt of the central triplet line only, performance may have benefitted from the surplus in task-relevant information provided by the presence (\ \

\-triplets) versus absence (\/\-triplets) of redundancy masking. We suggest that performance for uniform triplets with unidirectional flankers in Experiment 1 benefitted from the differential effect of redundancy masking, likely contributing to a similar performance level between uniform and alternating triplets. As the number of lines in \ \/- and \//-triplets were equally overestimated, tilt discrimination of the central line in Experiment 1 could not benefit from systematic differences in the number of perceived lines between both line configurations.

**General Discussion.**

We investigated whether the usual deleterious effect of high target-flanker similarity in crowding is dependent on the spatial configuration formed by target and flankers. With an orientation discrimination experiment (Experiment 1), we tested whetherflanker orientations influenced the usual advantage of opposite versus same contrast polarity flankers. Our findings demonstrated that the orientation of the flanking lines modulated the effect of contrast polarity. The polarity advantage was observed when flankers were upright and bidirectionally tilted. However, when flankers had unidirectionaltilts, the polarity advantage was absent: Performance did not differ between alternating and uniform triplets. We hypothesized that the absence of the polarity advantage was due to task-relevant information available in uniform triplets with unidirectional flankers, sufficiently advantageous to compensate for the usual cost of same contrast polarity flankers. In particular, we propose that configural cues elicited by uniform triplets with unidirectional flankers enabled similar performance as with alternating triplets. Since our findings did show the polarity advantage with upright and bidirectional flankers, we suggest that observers could not benefit from configural cues when uniform triplets had these flanker configurations.

To test these hypotheses, we investigated if emergent feature differences between the configurations could have contributed to the pattern of results observed in Experiment 1. In Experiment 2, we examined whether emergent features may have facilitated discriminating between triplets with unidirectional but not with bidirectional flankers. Inan odd-quadrant experiment, a standard paradigm to study emergent features (Pomerantz et al., 1977), observers indicated the line triplet with a central line tilt different from the other three triplets. Triplets identical to those of Experiment 1 were tested. As all four triplets had identical flankers on every trial, flanker configurations by themselves did not possess any informational value for the task at hand. The better discrimination between triplets with unidirectional flankers than between single lines indicated a clear configural superiority effect: Emergent features elicited by the target and flankers benefitted performance. With bidirectional flankers, there was no configural superiority effect. Performance was not better with than without flankers, showing no benefit of emergent features. Hence, emergent features seemed to affect performance when discriminating between triplets with unidirectional flankers but not with bidirectional flankers.

In Experiment 3, with an enumeration task, we investigated whether redundancy masking may have contributed to the good performance for uniform triplets with unidirectional flankers in Experiment 1. Observers were presented with three to five black tilted lines, and had to report the number of lines. We were particularly interested in how redundancy masking affected the enumeration of uniform triplets with uni- and bidirectional flankers, identical to the stimuli used in Experiment 1. Our findings showed that redundancy masking – as indicated by underreporting the number of lines – occurred for triplets of lines with similar tilts (\ \ \- and ///-triplets) but not for triplets containing opposite line tilts. Redundancy masking thus differentially affected triplets with unidirectional flankers: triplets of similarly tilted lines were underreported, while triplets with a central line of opposite tilt to both its flanking lines were overreported. With bidirectional flankers, redundancy masking did not affect performance, as both \ \/- and \//-triplets were overreported. Taken together, we propose that redundancy masking as well as emergent features provided additional task-relevant information when discriminating between uniform triplets with unidirectional flankers, enabling similar performance in uniform and alternating triplets with unidirectional flankers in Experiment 1.

In Experiment 1, for triplets with upright flankers, thresholds were clearly higher in the uniform condition than in the alternating condition. This finding replicated the usual advantage for conditions in which the flankers differed from the target compared to flankers similar to the target (e.g., Kooi et al., 1994; Manassi et al., 2012; Nazir, 1992; Põder, 2007; Sayim et al., 2008a). In particular, the results replicated the "polarity advantage" - flankers of opposite contrast polarity than the target interfered less with target discrimination than flankers of the same contrast polarity. The polarity advantage has been reported for various stimuli, including verniers (Sayim et al., 2008a), rotated Ts (Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Rummens & Sayim, 2021), and letters (Rosen & Pelli, 2015; Rummens & Sayim, 2019, 2021). In a previous study, vernier targets were flanked by upright lines, resembling the tilted targets flanked by upright flankers used here (Sayim et al., 2008a). The results were similar in the two studies: better offset discrimination of a vernier with opposite than with same contrast polarity flankers (Sayim et al., 2008a), and better orientation discrimination when upright flanking lines were of opposite contrast compared to same contrast polarity (present experiment). The same pattern of results was found when similar stimuli varied in color (red and green), in foveal (Sayim et al., 2008a) and peripheral (Manassi et al., 2012) vision. Hence, the effect of contrast polarity was as expected when flankers were upright: the orientation of a crowded line was better recognized with opposite compared to same contrast polarity flankers.

The polarity advantage was also revealed when flankers were bidirectional. However, the overall performance level in the bidirectional and upright condition differed greatly: tilt discrimination was much worse with bidirectional compared to upright flankers. In the uniform condition, thresholds were nearly twice as high for bidirectional as for upright flankers, and in the alternating condition, more than twice as high. In both conditions (upright and bidirectional), the *absolute* polarity advantage was comparable - thresholds were about 6 degrees lower with alternating than with uniform flankers. Consequently, the *relative* polarity advantage differed markedly: While thresholds for triplets with upright flankers were about half as high in the alternating condition compared to the uniform condition, the relative improvement in the bidirectional condition was only about 25 percent. In the bidirectional condition, the opposite contrast polarity of the flankers was clearly not sufficient to reduce thresholds to the same level as with upright flankers. Spatial factors that were counteracted only to a limited degree by opposite polarity flankers must underlie the still relatively poor performance with bidirectional flankers in the alternating condition.

The overall performance with unidirectional flankers was best, with thresholds in the uniform and alternating condition similarly low (7.14 and 8.31 degrees, respectively). Performance in the alternating condition here was similar as in the alternating condition with upright flankers. This result was not surprising and well in line with what would be expected if the polarity advantage did not strongly interact with orientation cues of the flankers. However, in contrast to upright flankers, thresholds were similarly low with uniform as with alternating contrast polarity in the unidirectional condition. Like the overall bad performance with bidirectional flankers, the high performance with uniform, unidirectional flankers must be due to (facilitating) spatial factors. If spatial factors and contrast polarity independently modulated performance, one prediction would be that their effects add up (as long as there were no ceiling or floor effects). Hence, performancewith unidirectional flankers would be expected to improve when the target was flanked by opposite instead of same contrast polarity flankers. However, this was not what we found. Instead, it seems that the spatial factors that improved performance with unidirectional compared to upright flankers were only helpful when the target and the flankers were of the same contrast polarity. Alternatively, opposite contrast polarity flankers simply may not have improved performance compared to same contrast polarity flankers because of a ceiling effect. However, since unflanked performance showed that there was still a large margin for improvement, we can exclude that the absence of the polarity advantage was due to ceiling performance.

The good performance for uniform triplets with unidirectional flankers assumes excellent tilt discrimination both when all lines had the same tilt direction as well as whenthe central line tilt was opposite to its flankers. Good performance for the central item of three tilted, parallel items has been shown before, with near perfect tilt discrimination of gabors (Petrov & Popple, 2007) and lines (Rummens & Sayim, 2021). An important factor for the good performance with \ \ \- and ///-triplets may well be display uniformity, which has been identified as a source of task-relevant information strong enough to counteract the usual cost of high target-flanker similarity (Melnik, Coates, & Sayim, 2020). Furthermore, the good performance for \/\- and /\/-triplets might be attributed to the absence of tilt uniformity that is easily detectable: when a crowded noise patch was replaced by a tilted Gabor, the change went unnoticed only when the tilt was similar but not when dissimilar to the tilt of the flanking Gabors (Greenwood, Bex, & Dakin, 2010). At the same time, the low thresholds for triplets with targets tilted in the opposite direction from the flankers (\/\- and /\/-triplets) are seemingly at odds with previous findings ofpoor performance in similar configurations (Petrov & Popple, 2007; Rummens & Sayim, 2021). For example, when observers reported the central item of a line triplet, performance was worse for \/\- and /\/-triplets than for all other configurations (Rummens& Sayim, 2021). However, unlike the present experiment where flanker tilts were kept constant within blocks, they were randomized in the previous study (Rummens & Sayim, 2021; see also Petrov &

Popple, 2007). Thus, with flankers of fixed orientation and onlytwo response alternatives, the absence of the \\\- or ///-triplet seemed sufficient to infer that the target line was of opposite tilt to its flankers, explaining the different performances for \/\- and /\/-triplets between these studies. Hence, tilt uniformity - and the absence of uniformity - may have provided strong configural cues that could be used to help target discrimination in uniform triplets with unidirectional flankers.

In Experiment 2, we investigated whether emergent features could explain the advantage of uniform tilts (present versus absent) for target discrimination when all lines were of the same contrast polarity. An emergent feature refers to the salient property of aspatial configuration resulting from the combination of basic features (Pomerantz & Cragin, 2014). Previous studies have already shown that specific line configurations may elicit emergent features such as parallelism or collinearity (Pomerantz, Chapman, Flynn, Noe, & Yingxue, 2017; Stupina, 2011). Crucially, the basic features themselves are perceived less promptly than the emergent configurations. Such configural superiority generally facilitates the identification of its constituting parts, as a tilted line was better identified when part of an organized object than within a less coherent context (Weisstein & Harris, 1974). Similarly, determining which of four lines had a different tilt compared to three other identical lines was facilitated when the addition of a non-informative line created four line pairs, of which three were parallel and one non-parallel (or vice versa) (Pomerantz, Chapman, Flynn, Noe, & Yingxue, 2017). These findings are well in line with the results of Experiment 2, showing a configural superiority effect for three-line configurations with unidirectional flankers. Specifically, discrimination between line tilts was superior when flankers were unidirectional compared to when flankers were absent. Since triplets with unidirectional flankers consisted either of all lines similarly tilted or of neighboring lines with opposite tilts, the presence versus absence of the emergent feature of parallelism seems to have facilitated discrimination, yielding better performance than with single lines. By contrast, emergent features did not benefit the discrimination between triplets with bidirectional flankers, as performance did not improve compared to single lines. Hence, configural cues – in particular the presence or absence of parallelism

- induced by a task-irrelevant context can strongly benefit discriminating between single line tilts.

In Experiment 3, we examined whether redundancy masking – in addition to emergent features – may have enhanced the discrimination between uniform \ \ \- and \/\- triplets, contributing to the low thresholds with unidirectional flankers in Experiment 1. Redundancy masking has been shown to strongly alter the perception of highly uniform stimuli (Sayim & Taylor, 2019; Yildirim, Coates, & Sayim, 2019, 2020, 2021). For example, when presented with three identical lines, observers frequently reported only two lines. Regularity, for instance in spacing, has been shown to strongly modulate redundancy masking, with irregular compared to regular spacing yielding less (or no) redundancy masking (Yildirim, Coates, & Sayim, 2020). The results of Experiment 3 revealed a similar dependence of redundancy masking on regularity in line tilts. Redundancy masking occurred only in triplets with uniformly tilted lines but not in triplets containing lines of opposite tilt: Observers frequently underestimated the number of lines in the repeating pattern of \ \ \- and ///-triplets, while the less repetitive \/\- and /\/-triplets were overreported. This difference in the perceived number of lines may have been a strong cue that facilitated the discrimination between uniform triplets with unidirectional flankers: perceiving two versus three lines could have been a systematic confound used to decide onthe target tilt. Importantly, redundancy masking has been shown to go hand in hand with acompression of space where the perceived spacing between lines is changed (Yildirim, Coates, & Sayim, 2019), possibly further contributing to high performance in discriminatingbetween \ \ \- and \/\-triplets. Since both line configurations with bidirectional flankers were similarly overreported, discrimination could not benefit from any cues provided by redundancy masking. Based on the results of Experiment 2 and 3, we propose that emergent features and redundancy masking provided observers with cues benefitting the discrimination between triplets with unidirectional flankers but not with bidirectional flankers.

In Experiment 1, we showed that flanker tilts strongly modulated crowding: Thresholds were highest with bidirectional flankers, and substantially lower for upright andunidirectional flankers. Here, we discuss whether these findings can be explained by prominent accounts of crowding. A simple pooling account of crowding would predict that the perception of the target tilt would result from an averaging process with the flankers (e.g., Greenwood, Bex, & Dakin, 2012; Parkes et al., 2001). With upright and bidirectional flankers both averaging to zero, interference by upright and bidirectional tilts should thus result in similar performance levels. However, the mean threshold for uniform triplets with upright flankers was 11.94°, while almost double (22.57°) for uniform triplets with bidirectional flankers (+20 and -20 degrees, respectively). Simple pooling can thus not account for the strongly divergent thresholds for upright and bidirectional flankers. Furthermore, it remains to be tested whether more complex pooling models such as the Texture Tiling Model ('TTM'; Balas, Nakano, & Rosenholtz, 2009; Keshvari & Rosenholtz, 2016; Rosenholtz, Yu, & Keshvari, 2019) would adequately capture the current results. Consistent with the similarity rule, TTM has been suggested to provide a better representation of a tilted line when flankers have a dissimilar compared to a similar orientation (Rosenholtz, Yu, & Keshvari, 2019). In Experiment 1, with only two response alternatives, the difference in representational quality may have facilitated discriminating between uniform triplets with unidirectional flankers, as \ \ \-triplets would be characterized by a worse representation of the central line and \/\-triplets by a better representation. Both for triplets with upright (|\| versus |/|) and bidirectional flankers (e.g., \ \/ versus \//), no systematic differences in the representation of the central line would be expected. While TTM could thus well predict the results of Experiment 1, there are some factors that may render TTM inadequate. In the current study, we proposed that the differential effect of redundancy masking may have facilitated discriminating between uniform triplets with unidirectional flankers. However, TTM does not seem to produce redundancy masking. For instance, when presented with three identical letters I, the output of TTM clearly preserves three I's (Keshvari & Rosenholtz, 2016). Similarly, most often three T's were preserved when creating mongrels of a T-trigram (Block, 2013). Therefore, it seems unlikely that TTM would predict redundancy masking to occur with uniform \ \ \- or ///-triplets, a stimulus that is highly similar to three repeating letters I. Furthermore, Bornet et al. (2021) recently highlighted another important limitation of TTM, namely its limited capability for capturing grouping cues. Such grouping cues (and how these interact) seem of utmost importance for explaining the current results.

Other accounts have proposed a prominent role for attention in crowding (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001), with limited attentional resolution impairing target individuation when flankers are at closer than critical spacing. Petrov & Popple (2007) suggested that only the pre-attentive feature contrast is preserved,while other information is lost during subsequent pooling of features within the attentionalregion. In their study, observers were instructed to report the tilts of three gabors, with each having a left- or rightward tilt. A larger amount of confusion errors was revealed between triplets that contained the same compared to a different number of orientation contrasts (OC; relative to the more outward element), suggesting that the number of OCs was available to observers. In the current study, orientation contrast (OC) may account for better performance when uniform triplets had unidirectional compared to both upright andbidirectional flankers. Indeed, discriminating between \ \ \- or ///-triplets (no OC) versus \/\- or /\/-triplets (two OCs) should be relatively easy, as the mere detection of an orientation contrast would be sufficient to infer the target tilt. Triplets with bidirectional flankers (\ \/ and \//; each with one OC) or upright flankers (|\| and |/|; each with two OCs) both share the same number of OCs, and should be less easily discriminated. Indeed, we observed worse performance for uniform triplets with bidirectional flankers compared to unidirectional flankers. However, performance for uniform triplets with upright flankers and with unidirectional flankers did not differ, suggesting that differences in the numberof OCs cannot adequately capture the results for uniform triplets. With alternating triplets, the similar thresholds for unidirectional (\ \ \- and \/\-triplets: zero vs two OCs) and upright flanker tilts (|\|- and |/|-triplets: both two OCs) suggested that OC was not predictive for performance with alternating triplets either. Furthermore, the number of feature contrasts in contrast polarity cannot account for the performance for alternating triplets. For all flanker configurations, adjacent lines in uniform versus alternating triplets were characterized by respectively zero and two alternations in contrast polarity. Therefore, if feature contrast predicted performance, contrast polarity would be expected to similarly affect all flanker configurations. Instead, we observed that the effect of contrast polarity depended on flanker tilt. Not only did the *relative* polarity advantage differ between upright and bidirectional flankers, the polarity advantage was even completely absent when flankers were unidirectional. Hence, contrast polarity and flanker tilt interactively determined performance. A simple additive combination of the effects of feature contrasts in separate dimensions cannot fully capture our results.

In crowding, flanker features are usually task-irrelevant and their integration detrimental. Any sufficient decrease of target-flanker integration would therefore be expected to benefit performance. Yet, the absence of the polarity advantage in uniform triplets with unidirectional flankers shown here suggests otherwise: the integration of flanker tilts seems to have benefitted performance to the extent that performance for alternating triplets was matched. Despite the task-irrelevancy of the flankers in the current study, high target-flanker similarity helped when flankers were unidirectional, and enabled a similar performance for uniform and alternating triplets. Our results suggest that the spatial configuration of uniform triplets with unidirectional flankers was informative on the tilt of the central target line, with the effects of emergent features and redundancy masking likely providing potent cues to override the similarity rule. When the triplets with unidirectional flankers consisted of alternating polarity lines, the reduction of stimulus uniformity in alternating compared to uniform triplets seems to have diminished the effect of emergent features. Emergent features, grouping, and Gestalts have been proposed to be strongly related: when elements group into a Gestalt and new features emerge, these features are perceived more promptly than its constituent basic features (Pomerantz & Cragin, 2014). The smaller configural superiority effect in the alternating compared to the uniform condition, as revealed in Experiment 2, seems to suggest that contrast reversals may decrease the presence of emergent features and weaken the grouping of elements into a Gestalt. Contrast reversals might therefore underlie the often-revealed worse identification of complex configurations when their uniformity is disrupted than when intact. Previous studies already suggested that the Gestalt is preserved when all parts have the same contrast polarity, but often appears qualitatively different when parts differ in contrast polarity. For instance, a convex target among concave distractors was detected more slowly when consisting of opposite versus same contrast polarity lines (Elder & Zucker, 1993; see Goldfarb & Treisman, 2011, for costs of disrupting uniformity by color). Furthermore, the search efficiency was similarly low when target and distractors were closed configurations of alternating polarity lines compared to open configurations, suggesting that perceptual closure was likely reduced for configurations with contrast-reversing contours. Similar costs of disrupted uniformity were revealed in word recognition, with worse identification of a peripheral word when word segments alternatedin contrast polarity than when all word segments had the same contrast polarity (Rummens& Sayim, 2019, see Pinna & Deiana, 2018, for costs of disrupting word uniformity by color).Hence, contrast reversals may have weakened the configural cues provided by triplets with unidirectional flankers, possibly contributing to the absence of the polarity advantage for alternating triplets with unidirectional flankers.

In sum, our results demonstrated that both orientation and contrast polarity strongly modulated crowding. Performance could not be explained by combining theseparate effects of the individual features, but was instead determined by the interaction between contrast polarity and flanker configuration. In particular, the polarity advantage differed in magnitude between bidirectional and upright flankers, and was eliminated with unidirectional flankers. The absence of the polarity advantage with unidirectional flankers suggested that, when triplet lines strongly grouped due to same contrast polarity, performance benefitted from a configural advantage that enabled a similar performance level as with opposite polarity flankers. Hence, strong grouping of the target with unidirectional flankers yielded high instead of the usual low performance. To explain the configural advantage, we attribute a pivotal role to redundancy masking and emergent features, as both factors seemed to enhance the availability of task-relevant information when flankers were unidirectional. Our findings show that compulsory integration of flanker and target features can either hurt or benefit performance, depending on task- relevant information provided by the spatial configuration. We propose that strong target- flanker grouping in crowding may benefit performance when target-relevant information emerges from target-flanker configurations.

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# Chapter 5:

# General Discussion

## 1. Summary

Crowding limits numerous visual tasks such as tilt discrimination (e.g. Andriessen & Bouma, 1976; Felisberti et al., 2005; Levi et al., 2002; Livne & Sagi, 2007, 2010; Parkes et al., 2001), letter identification (e.g. Bouma, 1970, 1973; Chung, 2007; Chung & Mansfield, 2009; Coates et al., 2019; Rosen & Pelli, 2015), and word recognition (e.g. Bernard et al., 2016; Pelli & Tillman, 2008). In the current dissertation, these tasks were used to test the generality of the similarity rule of crowding. In the first study (Chapter 2), I started with examining the effect of several feature contrasts (color, luminance, color/luminance combined, and contrast polarity) on the recognition of a crowded letter. With regard to letter recognition, the results showed the typical polarity advantage (e.g. Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994): A central trigram letter was better recognized when its flankers had the opposite rather than the same contrast polarity. Any benefit was absent when trigram letters alternated in color, luminance, or both compared to uniform trigrams without such alternations. Next, I measured peripheral word recognition when the same feature contrasts were applied to syllabic and non-syllabic word parts. Similar to letter recognition, word recognition did not benefit from alternations in color, luminance, or both compared to uniform words. Interestingly, when syllables or non-syllables alternated in contrast polarity, both conditions showed worse performance compared to when words were uniform in contrast polarity. Hence, the same feature contrast that benefitted the recognition of a single crowded letter was detrimental for word recognition when applied to multi-letter word parts.

In the second study (Chapter 3), I examined whether differences in selective attention between single letter and word recognition may account for the opposite effect of contrast polarity in both tasks. In three experiments, I compared the effect of contrast polarity between a single-item and full report paradigm, respectively requiring attentional selection of either a single or multiple crowded targets. Stimuli were three-item stimuli consisting of letters (Experiment 1), rotated Ts (Experiment 2), and tilted lines (Experiment 3). Stimuli were uniform or alternating in contrast polarity, with neighboring items having respectively the same or opposite contrast polarity. In single-item report, observers reported the left, central, or right item only; in full-report, all three items were reported from left to right. Experiment 1 and 2 revealed the typical polarity advantage, with superior performance for alternating compared to uniform stimuli when reporting only the central letter or the tilt of the central T. However, when all letters or Ts required reporting, any benefit of alternating over uniform stimuli was absent. Instead, the similarity rule was reversed in full report, as low versus high similarity between adjacent letters or rotated Ts yielded worse performance. In Experiment 3, the polarity advantage was surprisingly absent: When reporting the central line tilt only, performance was similar for triplets that were uniform or alternating in contrast polarity. In full report, contrast polarity did not affect performance either. The key findings revealed a reversal of the similarity rule under broad attention: the usual benefit of low target-flanker similarity was reversed when attention was needed towards multiple instead of a single crowded target.

In the third study (Chapter 4, Experiment 1), I probed the similarity rule when varying target-flanker differences on multiple dimensions – contrast polarity and flanker orientation. In particular, I measured tilt discrimination for central line (left or right) within line triplets. Flanker tilts were upright (||), unidirectional (\\ and //), or bidirectional (\/ and /\). Neighboring lines either had the same (uniform triplets) or opposite contrast polarity (alternating triplets). The polarity advantage was revealed with upright and bidirectional flankers, but, with unidirectional flankers, performance was similar for uniform and alternating triplets. Thus, contrast polarity and flanker tilt interactively determined crowding.

With two follow-up experiments, I aimed to elucidate which factors drove the interaction between contrast polarity and flanker orientation. First (Chapter 4, Experiment 2), I examined the potential role of emergent features for the absence of the polarity advantage with unidirectional flankers. To this aim, I measured performance in an odd-quadrant task, asking observers to indicate the unique line triplet out of the four triplets presented. The findings revealed better tilt discrimination for triplets with unidirectional flankers (e.g. \\\ versus \/\) than between single lines (\ versus /), indicating a configural superiority effect. Hence, the addition of non-informative, unidirectional flanking lines yielded salient properties – emergent features – that facilitated discriminating between line tilts. Interestingly, the configural superiority effect revealed for triplets with unidirectional flankers was larger when lines had the same contrast polarity compared to when alternating in contrast polarity. With bidirectional flankers, there was no configural superiority effect, and any benefit of emergent features was absent. Instead, the addition of bidirectional flankers deteriorated performance compared to single lines. With bidirectional flankers, discrimination was better for alternating triplets than for uniform triplets. Second (Chapter 4, Experiment 3), I tested whether redundancy masking may have contributed to the similar performance between uniform and alternating triplets with unidirectional flankers. Observers were asked to enumerate the number of lines when presented with three to five tilted lines. Only the three-line stimuli – identical to those of Experiment 1 - were of interest. Redundancy masking only affected triplets of similarly tilted lines (\\\ and ///): three near-parallel lines were on average underreported, suggesting that observers often saw only two lines when three lines were presented. Redundancy masking did not occur for line triplets including opposite tilts. Taken together, the findings of the follow-up experiments suggest that emergent features and redundancy masking facilitated discriminating between uniform triplets when flanker tilts were unidirectional (but not when bidirectional). Spatial configurations of uniform triplets with unidirectional flankers seemed to have released sufficient task-relevant information to bring performance to the same level as for alternating triplets.

Overall, these findings strongly challenge the generality of the similarity rule, with uniform stimuli – despite stronger crowding - yielding similar (Chapter 4) or even better (Chapter 2 and 3) performance than less uniform stimuli. Attentional and configural factors can counteract the usual deleterious effect of strong target-flanker grouping in crowding.

## 2. Benefits of stimulus uniformity

When the task required identifying multiple letters, stimulus uniformity was beneficial compared to the absence thereof. Peripheral word recognition deteriorated when multi-letter word segments – syllables or non-syllables –

alternated in contrast polarity compared to when all word parts had the same contrast polarity (see Chapter 2). Similarly, the identification of three random letters or rotated Ts was superior when trigrams consisted of same compared to alternating contrast polarity letters (see Chapter 3). Typically, the similarity rule of crowding predicts the opposite pattern, with worse performance for uniform compared to less uniform stimuli. However, with multiple instead of a single task-relevant item, the beneficial side of stimulus uniformity prevailed.

Previous crowding studies already suggested that high similarity between adjacent items may be less detrimental when reporting all instead of the central item only. For instance, when presented with a trigram of three black letters, recognition of the central letter was superior when all letters instead of only the central one were task-relevant (Huckauf & Heller, 2002; but see Zhang et al., 2012). Furthermore, in a control experiment, Chung & Mansfield (2009) showed that the usual benefit of opposite relative to same contrast polarity flankers when reporting the central trigram letter only was greatly reduced in full report. The latter finding closely resembles the results of Experiment 1 and 2 in Chapter 3. When observers reported the central item of three random letters (Experiment 1) or rotated Ts (Experiment 2), performance was – as expected - better with opposite compared to same contrast polarity flankers. However, in full report, performance with regard to the central letter or rotated T did not differ between uniform and alternating stimuli. Moreover, when accuracies for all three letter positions (left, central, and right) were combined, full report performance was better for uniform compared to alternating trigrams.

With regard to word recognition, performance was worse when adjacent syllables or non-syllables alternated in contrast polarity compared to when all word parts had the same contrast polarity (see Chapter 2). Again, with a task that required the recognition of multiple letters, superior performance was found for uniform stimuli compared to stimuli with disrupted uniformity. Many other studies on word recognition and reading also highlighted the advantageous character of word uniformity. Coltheart & Freeman (1974) revealed impaired recognition for words consisting of a mix of upper and lower case letters compared to words of all upper or of all lower case letters. Similarly, reporting a string of multiple letters was more accurate when all belonged to the same font than when two fonts were mixed within a string (Sanocki, 1988). Furthermore, Pinna (2010) showed faster text reading when whole words alternated in color than when word letters alternated in color. The findings of Pinna (2010) are consistent with those of Chung & Mansfield (2009), as both studies showed that reducing the similarity between neighboring letters – respectively by alternations in color or in contrast polarity - did not improve reading performance.

However, some studies did reveal beneficial effects on word recognition when making multi-letter word segments or individual word letters more distinct. For instance, syllable segmentation by color has been suggested to improve peripheral word recognition (Bernard, Calabrèse, & Castet, 2014). Several task differences might account for the divergent results between their study and the current word recognition experiment (Chapter 2, Experiment 2). Observers in the study of Bernard and colleagues (2014) were hindered by a central scotoma. Therefore, a strategy in terms of eye movements could be developed, with improved syllable segmentation likely providing useful positional cues. No such strategy was possible here. In addition, the role of syllables in word recognition may differ between German (the current study) and Romance languages (their study) (Conrad & Jacobs, 2004), as, for instance, the position of syllable boundaries is less clear in German (Wiese, 2000). Reduced crowding between letters did facilitate word identification when letters were presented in a font with reduced inter-letter similarity (Eido) compared to a standard font (Courier New) (Bernard, Aguilar, & Castet, 2016). This benefit was attributed to weaker crowding: the number of unrecognized letters was on average lower when presented with crowded trigram letters in Eido than in Courier New. Possibly, in order for a reduction of crowding to benefit word recognition and reading, an optimal balance is needed between letter distinctiveness and stimulus uniformity. Consistent with this idea is that a good font - in terms of legibility - requires letters that are distinct yet uniform (Cheng, 2005). The importance of stimulus uniformity for optimal reading is well-known by font designers: “Within words, a letter should never stand out; it should cohere with neighboring letters, in order to better form a word unit and sublexical units as well” (Sanocki & Dyson, 2012). The reversals of the similarity rule revealed with multiple crowded targets suggest that the potential benefit of alternating contrast polarity - and reduced crowding – was counteracted by costs of disrupted uniformity.

## 3. Exceptions to the similarity rule

All three studies included in this dissertation revealed exceptions the similarity rule, both when multiple crowded items required attentional selection (Chapter 2 and 3) and when the spatial configuration formed by target and flankers was informative on target identity (Chapter 4). In the next two paragraphs, these factors are discussed in more detail.

### Attention

In the first (Chapter 2, Experiment 1) and second study (Chapter 3, Experiment 1 and 2) confirmations of the similarity rule were revealed, as the polarity advantage applied when the central item of a letter or rotated T trigram required reporting. However, when observers reported all letters, rotated Ts, or whole words, performance was worse when stimuli alternated in contrast polarity than when stimuli were uniform in contrast polarity. The differential effect of stimulus uniformity between single-item and full report paradigms may suggest a role for spatial attention: multiple crowded targets versus a single one usually take in more space and thus require attention over a broader region. Previous research already showed that key properties of crowding – typically found under focused attention – may no longer apply when broader attention is needed. In that regard, the inward-outward anisotropy of crowding has been shown under focused but not under diffused attention (Petrov & Meleshkevich, 2011). In the study by Petrov & Meleshkevich (2011), observers indicated whether a crowded gabor with certain tilt appeared in the left or right hemifield. The spatial probability of the target location was varied: the target appeared at the same location on every trial in the focused attention condition, and randomly at one of three locations with equal probability in the diffused attention condition. In the same study, another attentional modulation of crowding was found: the inward-outward anisotropy was reversed when attention was biased inwards by a foveal cue (for three out of four participants; Petrov & Meleshkevich, 2011). The current findings show that spatial attention – when varied by the number of task-relevant items – can modulate another key property of crowding, the similarity rule.

Furthermore, findings from studies on object-based attention (for reviews see Chen, 2012; Scholl, 2001) may provide insight in the divergent effect of stimulus uniformity. Objects are formed when visual information is organized into coherent units based on grouping cues such as similarity or proximity (Kimchi et al., 2016). Important evidence in favor of object-based attention stems from 'same-object advantages' (SOA), as indicated by faster target processing when the target location was invalidly cued on the same versus other object (Egly & Driver, 1994). SOAs have been attributed to an automatical spreading of attention within but not between objects (Davis et al., 2000; Vecera & Farah, 1994). In the current dissertation, stimuli comprising same rather than alternating contrast polarity items can be considered more coherent perceptual objects. The automatically broadening of attention within the whole object seems beneficial when all stimulus elements are task-relevant but costly when only a single element is. This pattern strikingly resembles the ambivalent effect of stimulus uniformity revealed in Chapter 2 and 3.

**Configural cues**

In Chapter 3, the findings of the second study revealed the polarity advantage with letters, rotated Ts, but not with tilted lines. Most likely, the limited stimulus complexity of the line triplets did not underlie the absence of the polarity advantage, as the polarity advantage has been shown with stimuli of similar complexity. Particularly, offset discrimination for a crowded vernier was superior when flanked by opposite compared to same contrast polarity lines (Sayim et al., 2008; for similar effects with color see Manassi et al., 2012). To explain the absence of the polarity advantage with tilted lines, I hypothesized that the spatial configuration between the target and flanking lines may have elicited configural cues, contributing to the similar performances between uniform and alternating stimuli. More specifically, a flanker and a target line were either parallel (\\ or //) or not (\/ or /\). Therefore, the presence or absence of the emergent feature of parallelism (Stupina, 2011) could have been particularly helpful when deciding on the tilt of the central line within the triplet. The idea that emergent features elicited by the target and irrelevant flankers could benefit performance in a crowding task was further explored in Chapter 4.

In Chapter 4, the main finding (Experiment 1) showed that the usual benefit of opposite versus same contrast polarity flankers was dependent on flanker orientation. The polarity advantage was found for line triplets with upright and bidirectional flankers, but was absent with unidirectional flankers. Based on the findings of two additional experiments, it seems that configural cues – emergent features and the susceptibility to redundancy masking – elicited by three tilted lines likely played a role in the similar thresholds found for uniform and alternating triplets with unidirectional flankers.

These findings are well in line with previous studies showing a reversal of crowding properties when spatial configurations of target and flankers had particular emergent features (Melnik et al., 2018, 2020). When a target chevron (pointing up or down) was flanked by a chevron on each side, performance at closer compared to larger spacing was surprisingly better when the target and its upper, critical flanker formed a diamond shape or both pointed upwards (Melnik et al., 2018). When the critical flanker pointed downwards, both combinations with the target (i.e., X or both chevrons pointing down) showed the usual better performance with increasing separation. This pattern of results was more pronounced when observers were informed about the possible configurations of the target and the critical flanker. The differential effect of target-flanker spacing was attributed to emergent features of the target and the (critical) flanker. Furthermore, when the whole configuration (i.e. target and critical flanker) required reporting, the reversal of the usual stronger crowding at closer target-flanker spacing was found for all configurations (diamond; up-up; X; down-down). The decrease in performance with increasing spacing differed between configurations, again suggesting a role for the strength of the grouping and emergent features of the target and the critical flanker. In short, the effect of target-flanker spacing was dependent on the spatial configuration formed by the target and the critical flanker. Another study by the same researchers (Melnik et al., 2020) showed a reversal of the similarity rule, with weaker crowding of a diamond-shaped target compared to an X-shaped target when flanked by diamonds. With Xs as flankers, the similarity rule held: Performance was better with a diamond target compared to an X target. When observers subsequently judged whether all items within the display were the same or not, better uniformity judgments were found for displays of all diamonds compared to displays of all Xs. Thus, display uniformity may have contributed to the reversal of the similarity rule, providing a useful cue when all items were diamonds but not when all items were Xs. The current findings (Chapter 4, Experiment 1) showed a similar dependence of the similarity rule on the emergent features present within the display. The uniformity of the display likely acted as an important source of task-relevant information as well, with its presence

(\\\- and ///-triplets) versus absence (\/\- and /\/-triplets) facilitating the discrimination between triplets with unidirectional flankers.

## 4. Models of crowding

Here, we discuss the compatibility of the current findings with the dominant theories of crowding.

Simple pooling models propose that crowding results from a compulsory integration of target and flanker features (e.g. Greenwood et al., 2009, 2010; Parkes et al., 2001). Consistent with a pooling account, Parkes et al. (2001) suggested that crowding may reflect compulsory averaging, as the mean orientation of tilted gabors was available to observers while the orientation of the single target gabor was not (but see Ester et al., 2014). If the average orientation of target and flankers determined performance, one would predict similar performance levels for uniform triplets with upright flankers and symmetrical bidirectional flankers (Chapter 4, Experiment 1). However, the current findings clearly showed otherwise, with far better performance (almost half the threshold) with upright compared to bidirectional flankers.

It is unclear whether more complex pooling models such the Texture Tiling Model (TTM; Balas et al., 2009; Keshvari & Rosenholtz, 2016; Rosenholtz et al., 2012, 2019) could account for the current results. To answer this question, the current studies could be redone using mongrel versions of the original stimuli as outputted by TTM. For the time being, I will confine myself to speculating whether or not TTM can explain the current results, for example those of Experiment 1 of the third study (Chapter 4). In this experiment, thresholds for the central line tilt greatly differed between flanker configurations. Performance was best for triplets with unidirectional flankers, worst with bidirectional flankers, and performance with upright flankers was sitting in between both. I proposed that the excellent performance for triplets with unidirectional flankers greatly relied on emergent features and redundancy masking, making it easier to discriminate between triplets with unidirectional flankers but not between the other triplets included. An explanation in terms of emergent features and redundancy masking does not seem compatible with TTM. First, TTM does not successfully capture effects of grouping in crowding (Bornet et al., 2021). Therefore, although TTM produces the polarity advantage (Rosenholtz et al., 2019), it may fail to predict the interaction between contrast polarity and configural grouping revealed in Experiment 1. Second, TTM does not support redundancy masking: when presented with three identical letters I, TTM clearly preserves three I's (Keshvari & Rosenholtz, 2016). However, because identical items are more texture-like, and more adequately captured by summary statistics, triplets of identical items are better represented then when comprising different items. With TTM, the representation of three similarly tilted lines (e.g. \\\) is thus likely better than of triplets with the central line tilt opposite to the flanker tilts (e.g. \/\). By contrast, TTM has been suggested to produce better representations of a central line when it flankers have less versus more similar orientations, predicting typical benefits of low target-flanker similarity (Rosenholtz et al., 2019). Despite these seemingly contradictory predictions of high target-flanker similarity yielding either a better or a worse stimulus representation than low similarity, a difference in representational quality between high and low target-flanker similarity is apparent with both alternatives. With only two response options, this difference in representational quality might account for the excellent performance for triplets with unidirectional flankers. Both for triplets with upright (|\| versus |/|) and bidirectional flankers (e.g., \\/ versus \//), no systematic differences in the representation of the central line would be expected.

With a full-report paradigm, Petrov et al. (2007) measured tilt discrimination for stimuli comprising three gabors with a 45° left- or rightward slant. An anisotropic feature contrast model was proposed to account for their results, incorporating the inward-outward asymmetry present in their data. Importantly, triplets were confused more often when having a similar rather than dissimilar number of orientation contrasts (OC; relative to the more outward stimulus element). Indeed, the most frequent confusion occurred between \\/- and \//-triplets each having one OC. Furthermore, \\\-triplets were never confused with other triplets as it was the only configuration without OC. Their findings were explained by an attentional account of crowding: OCs 'pop-out', and are detected pre-attentively, while other information is lost during subsequent pooling in the attentional stage. In one of the conditions of Experiment 3 of the second study (Chapter 3), a similar full-report paradigm was used, measuring tilt discrimination for three randomly tilted lines. As in Petrov et al. (2007), \\/-triplets were confused most frequently with \//-triplets (on 26 percent of the trials). However, in contrast with Petrov and colleagues (2007), similar performance for inward and outward lines did not suggest inward-outward anisotropy. Moreover, when presented with \/\- or /\/-triplets (both two OCs), observers reported \\\- or ///-triplets (both no OCs) in 14 percent of the trials. Compared to Petrov et al. (2007), the current study included small target-flanker differences in terms of orientation, which may have promoted assimilation of the target tilt towards the flanker tilts (Solomon et al., 2004; for similar results in the fovea Kapadia et al., 2000). Hence, an anisotropic attentional model preserving only feature contrast does not seem to adequately explain these results. Nevertheless, as already discussed previously, the current findings do suggest an intimate link between attention and crowding.

## 5. Conclusion

The similarity rule of crowding is typically evidenced by the better recognition of a single, crowded target when surrounded by flankers that strongly differ on a particular dimension. However, many everyday tasks are less artificially constrained than standard crowding paradigms. For instance, objects in a visual scene often vary on multiple dimensions, or several items instead of a single one are relevant for our behavioral goals. The findings of the current dissertation suggest that the similarity rule might not generalize to such 'ecologically-valid' conditions. The effect of a typical target-flanker similarity manipulation – i.e. contrast polarity – was shown to depend on whether the task required attentional selection of a single or multiple crowded targets. When multiple items required recognition, a reversal of the similarity rule was found: high compared to low similarity between neighboring items improved performance, suggesting benefits of uniformity under broad attention. Moreover, when targets and flankers varied on several dimensions, they interactively determined crowding. In particular, the polarity advantage was found for some but not all spatial configurations formed by tilted lines. Overall, the validity of key properties of crowding seems strongly dependent on attentional and configural factors.

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