









Figure 1. Upper panel: Results are plotted in terms of threshold elevation of the single vernier condition, i.e., thresholds of the flanking conditions divided by the threshold of the unflanked condition (dashed lines). Error bars indicate  $\pm 1$  standard error. A threshold elevation of 1.0 indicates no crowding; values larger than 1.0 indicate crowding. Performance improved when the number of short and long flankers increased (a and c), and stayed on a constant level for equal-length flankers (b). In contrast, performance deteriorated when the number of short, jittered flankers increased (d). In this condition, 16 flankers yielded a 26-fold increase in thresholds. Please note different scales of the y axis. Lower panel: Subjective ratings. Observers were asked to rate how much the vernier stands out from the flankers on a scale











We propose that regularity of the alternating lines yields grouping of the vernier with the flankers. Reading speed of alternating black–white letters is as slow as with either black or white letters, possibly, because letters group in all the three conditions (Chung & Mansfield, 2009). The centroid hypothesis cannot explain these results because in Figure 4b, d, e, and f, centroids of the flankers are at the same position but threshold elevations are substantially different.

Subjective ratings (Figure 4, lower panel) are qualitatively very similar to discrimination thresholds with the exception of Figure 4f. It seems that observers perceive the target vernier to group with the flankers. Still, thresholds are low because the spacing between flankers, particularly between target vernier and direct flankers, is wide. Alternatively, small receptive fields could have been used to discriminate the vernier offset (Figure 4, upper panel) and large receptive fields to perceive the global stimulus configuration (Figure 4, lower panel), thus yielding discrepancies between subjective ratings and threshold values.

## General discussion

We have shown that grouping is a key feature of crowding. Crowding with verniers can yield remarkable threshold elevations larger than a factor of 26 (Figure 1d). Crowding with verniers shows the typical inward–outward asymmetry (however, such asymmetries are also found in masking, see Jiang & Chun, 2001). Our findings with peripheral vernier stimuli are very similar to previous findings with foveally presented verniers (Malania et al., 2007; Sayim et al., 2008, 2010). Very similar effects of grouping were also found with Gabor stimuli (Saarela et al., 2009; Saarela et al., 2010) and letters (Saarela et al., 2010) presented in the periphery.

### Centroids

One of our main findings is that crowding can decrease, stay constant, or increase when the number of flankers or their length increases, i.e., the number and length of flankers per se does not predict crowding strength (Figure 1). When flankers were longer or shorter than the target vernier, crowding decreased when more flankers were presented (Figure 1a and c). When flankers were of the same length, crowding virtually did not change (Figure 1b). Crowding strongly increased when flankers were jittered (Figure 1d), even though crowding decreased for the very same flankers when not jittered (jittered vs. short condition). We previously obtained virtually the very same results with foveal stimuli (Malania et al., 2007). All other previous

studies have, to the best of our knowledge, shown that increases in flanker number increase crowding or leave it unchanged (Felisberti, Solomon, & Morgan, 2005; Parkes et al., 2001; Pelli et al., 2004; Pöder & Wagemans, 2007; Strasburger, Harvey, & Rentschler, 1991).

Based on the results in foveal vision, we proposed that grouping plays a key role in crowding (Malania et al., 2007). Crowding is weak or absent when the target ungroups from the flankers. Crowding increases when target and flankers group.

Levi and Carney (2009) also found that increases in flanker size decreases crowding. They proposed that bigger is better and explained their findings by the distance between the target and the centroids of the flankers (rather than between the inner contours of the flankers and the outer contours of the target, as in Bouma’s law). However, increasing the size or number of flankers does not always lead to a reduction of crowding. The centroids in the short, equal, and long multi-flanker conditions of the present study are always the same, but performance varies nonmonotonically from short to equal to long flankers (Figure 1a through c). Likewise, the centroids are identical in the configurations of Figure 3b through d, but performance varies strongly. In addition, the centroids for the alternated color grating and the wider red and green gratings are nearly identical, but performance is clearly not (Figure 4d through f). Also in Levi and Carney (2009), performance did not improve when more than eight flankers were presented and their size increased. Hence, bigger is not always better. We propose that bigger is better when increases in the number or size of the flankers lead to ungrouping of the target from the flankers. Bigger is worse when it enhances grouping of the target with the flankers (Malania et al., 2007; Saarela et al., 2009; Saarela et al., 2010; Sayim et al., 2008, 2010, 2011).

According to the centroid hypothesis (Levi & Carney, 2009), the centroids of the flanker arrays to the right and left of the vernier determine crowding. It might be argued that this is only true when the vernier ungroups from the flankers. When vernier and flankers group, as for example, in the equal-length condition, there is only one grouped configuration, i.e., one center of gravity, and hence, performance deteriorates. However, such explanation presupposes a grouping operation, such as “flanker arrays to the left and right.” Hence, grouping plays a key role in explaining crowding strength.

### Pooling

Bouma’s law and the centroid hypothesis operate on the level of stimulus rendering or stimulus coordinates. The grouping account operates on the level of

perceptual organization. On the level of neural explanations, pooling is one of the key components. In standard pooling models of crowding (Pelli et al., 2004; Wilkinson et al., 1997), a visual stimulus is first processed at basic feature detectors, which then project to higher level feature detectors. Higher level detectors combine the outputs of a number of low level detectors and thus, position information of the features is lost. How exactly features are pooled is usually not exactly specified.

In very simple pooling models, features of nearby elements are pooled. Another option is that pooling occurs only amongst neurons that code for the same or similar features in accordance with the notion that crowding is weaker when target and flankers are dissimilar (Kooi et al., 1994; Saarela et al., 2009; Saarela et al., 2010; Sayim et al., 2008, 2010). Such pooling models can explain why short and long single flankers yield better performance than single, equal-length flankers (Parkes et al., 2001; van den Berg, Roerdink, & Cornelissen, 2010). However, such models fail to explain why performance improves when the number of long and short flankers increases. These multi-flanker array configurations contain the very same single flankers next to the vernier target. The same holds true in [Experiment 2](#), where single flankers become part of figures, i.e., good Gestalts. Low level feature detectors are triggered by these flankers in the same way whether or not they are part of good Gestalts. Hence, performance should not improve, but it does. Very similar results were found for Gabor stimuli in peripheral vision (Saarela et al., 2009) where multi-flanker configurations of long and short Gabor flankers led to better performance than equal-length flanker configurations.

One recent study showed that remote flankers, which crowd very little themselves, exert strong nonadditive increases of crowding when combined with flankers closer to the target (supercrowding; Vickery, Shim, Chakravarthi, Jiang, & Luedeman, 2009). In this respect, the results of [Experiments 1A](#) and [3](#) also show very similar, nonlinear crowding effects. In [Experiment 3](#), the wider spaced red and green arrays of flankers crowded very little, but their combination led to strong crowding by a factor of 14 ([Figure 4](#)).

## Grouping

Only very few studies have investigated the role of grouping in crowding. In general, most research on crowding uses one target that is flanked by a pair of flankers. Multi-element or complex flankers were rarely used in the past even though the grouping idea is not new. Wolford and Chambers (1983) showed that when

flankers group, crowding is reduced (see also Banks & Prinzmetal, 1976).

Livne and Sagi (2007) proposed that *flanker–flanker* grouping determines crowding (see also Livne & Sagi, 2010). With the same set of stimuli, but in different configurations, Chakravarthi and Pelli (2011) showed evidence that only *local target–flanker* binding matters, i.e., the *global flanker–flanker* configuration does not matter—an interpretation countered by Livne and Sagi (2011). Our results with vernier stimuli favor an explanation in terms of global target–flanker grouping because adding flankers can weaken crowding, and good Gestalt and regularity matter ([Figures 1, 3, and 4](#); Malania et al., 2007; Saarela et al., 2009; Sayim et al., 2010, 2011; but see Felisberti et al., 2005).

As we have shown, grouping plays a key role in crowding but is neither sufficient nor necessary. For example, observers grouped the red flankers in [Figure 4f](#); however, the flankers do not crowd because the spacing is too wide. In general, remote flankers can group with a target without crowding. Interestingly, remote flankers that group, but do not crowd, can still modulate target perception (see also Sayim & Cavanagh, 2011). Hence, grouping is not sufficient. Performance deteriorates when flanker luminance or contrast increases (Dombrowe, Hermens, Francis, & Herzog, 2009; Kooi et al., 1994), even though this leads to ungrouping by luminance/contrast dissimilarity. Hence, grouping is not necessary.

Gestalt rules explain grouping well for simple stimulus configurations but often fail when more than one Gestalt rule applies. Likewise with crowding. For example, proximity is a strong Gestalt cue and, indeed, performance usually improves when flankers are moved away from the target (in this respect, Bouma's law can be seen also as a description on the level of perceptual organization in addition to the level of stimulus layout). However, in peripheral vision, Saarela et al. (2010) showed that *decreasing* proximity between the target and the closest flankers *increased* crowding when the entire flanker configuration became regular by this manipulation. Hence, it seems that the Gestalt rule of good Gestalt or Pragnanz counteracted proximity. In addition, it is often unclear whether the Gestalt rules operate on a stimulus description level (e.g., proximity) or on a level of perceptual organization (good Gestalt). For this reason, we propose that subjective measurements of grouping must be determined in addition to accuracy measurements.

Grouping is a key factor in crowding. However, grouping itself cannot explain why performance deteriorates when target and flankers group. Grouping needs to be linked to neural mechanisms such as inhibition, feature pooling, or limited attentional resolution (He, Cavanagh, & Intriligator, 1996; Strasburger, 2005). Mechanisms are needed explaining why,

for example, (location) information of features is *lost* (Huckauf & Heller, 2002). Thus, how can grouping be linked to neural mechanisms? As mentioned, simple pooling or inhibition models cannot explain the results presented here.

It may well be that grouping precedes crowding, i.e., the visual system first groups elements into wholes and then within each group a crowding mechanism operates (Parkes et al., 2001). However, why should this be the case? Feature pooling across the visual field can be explained by receptive fields properties. Pooling within groups cannot because grouping between elements can easily change while receptive fields do not. Models are needed that take flexible element bindings into account.

May and Hess (2007) proposed such a model in which two, rather than one, mechanisms explain contour integration and crowding. A collinear and a noncollinear binding mechanism compete about the ownership of elements. Grouping of an element to one group can ungroup the elements from another group. This model also explained crowding of letters well. Whereas such a model can possibly not be directly applied to our vernier stimuli, the model provides a framework of how global aspects of crowding emerge by the competition of two mechanisms. Our results and the results of contour integration also show strong phenomenological similarities. Collinear Gabor “snakes” are perceived as clearly different from flanking Gabors. Likewise, the single flankers in Figure 3 are not seen as flankers but as a part of a rectangle—and they do not group with the vernier anymore. However, the exact characteristics of the underlying neural computations remain largely unknown for the moment.

Another question is *when* crowding occurs. Crowding may occur as a consequence of grouping or *during* grouping. For example, models with recurrent lateral inhibition have been proven to explain a large variety of grouping effects in backward masking that show the very same characteristics reported here in crowding (Hermens, Luksys, Gerstner, Herzog, & Ernst, 2008; Hermens, Scharnowski, & Herzog, 2009). In these models, representations of remote flankers, even when not connected directly, can influence each other via intermediate flanker representations in a time consuming manner (Hermens et al., 2008; Herzog, Ernst, Etzold, & Eurich, 2003). Applied to the stimuli of this contribution, activity of the vernier is inhibited for equal-length flankers because the vernier is in the center of a redundant structure. In long and short multi-flanker configurations, the flankers inhibit each other but not the vernier, and hence performance is better than in equal-length conditions.

Future work has to link descriptions on the level of perceptual organization (grouping) with explanations on the neural level (recurrent inhibition). For the

moment, we propose that one of the best predictors of the strength of crowding is the extent to which target and flanking elements are grouped. However, the ultimate goal is to provide a model that links all levels of explanations.

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