Redundancy masking: The loss of repeated items in crowded peripheral vision

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Crowding is the deterioration of target identification in the presence of neighboring objects. Recent studies using appearance-based methods showed that the perceived number of target elements is often diminished in crowding. Here we introduce a related type of diminishment in repeating patterns (sets of parallel lines), which we term "redundancy masking." In four experiments, observers were presented with arrays of small numbers of lines centered at 10° eccentricity. The task was to indicate the number of lines. In Experiment 1, spatial characteristics of redundancy masking were examined by varying the inter-line spacing. We found that redundancy masking decreased with increasing inter-line spacing and ceased at spacings of approximately 0.25 times the eccentricity. In Experiment 2, we assessed whether the strength of redundancy masking differed between radial and tangential arrangements of elements as it does in crowding. Redundancy masking was strong with radially arranged lines (horizontally arranged vertical lines), and absent with tangentially arranged lines (vertically arranged horizontal lines). In Experiment 3, we investigated whether target size (line width and length) modulated redundancy masking. There was an effect of width: Thinner lines yielded stronger redundancy masking. We did not find any differences between the tested line lengths. In Experiment 4, we varied the regularity of the line arrays by vertically or horizontally jittering the positions of the lines. Redundancy masking was strongest with regular spacings and weakened with decreasing regularity. Our experiments show under which conditions whole items are lost in crowded displays, and how this redundancy masking resembles—and partly diverges from—crowded identification. We suggest that redundancy masking is a contributor to the deterioration of performance in crowded displays with redundant patterns.

Introduction

Crowding is the deterioration of target identification by neighboring objects. For example, a target letter is more difficult to identify when flanked by letters ("flankers"). Crowding is particularly pronounced in the peripheral visual field (Bouma, 1970; Bouma, 1973; He, Cavanagh, & Intriligator, 1996; Levi, Hariharan, & Klein, 2002; Levi, Klein, & Aitsebaomo, 1985; Pelli, Palomares, & Majaj, 2004; Strasburger, Harvey, & Rentschler, 1991), but also occurs in foveal vision (Coates, Levi, Touch, & Sabesan, 2018; Flom, Weymouth, & Kahneman, 1963; Liu & Arditi, 2000; Malania, Herzog, & Westheimer, 2007; Sayim, Westheimer, & Herzog, 2008; Sayim, Westheimer, & Herzog, 2010; Sayim, Westheimer, & Herzog, 2011). There are several key factors that determine the strength of crowding, including target-flanker spacing (Bouma, 1970; Bouma, 1973; Toet & Levi, 1992), similarity (Chung, Levi, & Legge, 2001; Kooi, Toet, Tripathy, & Levi, 1994; Levi et al., 2002; Nazir, 1992; Põder, 2006; Sayim et al., 2008), and grouping (Banks, Larsson, & Prinzmetal, 1979; Banks & White, 1984; Livne & Sagi, 2007; Manassi, Sayim, & Herzog, 2012; Manassi, Sayim, & Herzog, 2013; Melnik, Coates, & Sayim, 2018; Saarela, Sayim, Westheimer, & Herzog, 2009; Sayim et al., 2010, Sayim et al., 2011; Sayim, Greenwood, & Cavanagh, 2014; Wolford & Chambers, 1983).

Citation: Yildirim, F. Z., Coates, D. R., & Sayim, B. (2020). Redundancy masking: The loss of repeated items in crowded peripheral vision. *Journal of Vision*, *20*(4):14, 1–20, https://doi.org/10.1167/jov.20.4.14.

https://doi.org/10.1167/jov.20.4.14 Received March 11, 2019; published April 24, 2020 ISSN 1534-7362

Figure 1. Illustration of redundancy masking. When fixating the fixation cross on the left, observers may be able to identify the repeating letter T, but have difficulty determining whether there are two or three Ts.

Crowding not only deteriorates target identification but also changes its appearance (Greenwood, Bex, & Dakin, 2010; Korte, 1923; Sayim & Cavanagh, 2013; Sayim & Wagemans, 2017). A number of recent studies used appearance-based methods to characterize in detail how target appearance changed in crowding (Coates, Wagemans, & Sayim, 2017; Sayim & Taylor, 2019; Sayim & Wagemans, 2017). One of the central findings of these studies was that observers perceived fewer elements than were presented ("omission errors"; Coates et al., 2017; Sayim, Myin, & Van Uytven, 2015; Sayim & Wagemans, 2017; see also Korte, 1923). For example, when asked to draw crowded letters and letter-like stimuli presented in the periphery, participants often omitted presented target elements (Sayim & Wagemans, 2017). Importantly, the omission error rate depended on crowding strength, with more omissions under strong compared with weak crowding (Sayim & Wagemans, 2017). Similar omissions were also found with stimuli of higher complexity such as the Rey-Osterrieth figure (Coates et al., 2017), abstract paintings (Sayim et al., 2015), and letter strings in which participants frequently reported fewer letters than were presented (Liu & Arditi, 2000; Korte, 1923; see also Strasburger, 2014; Strasburger, Rentschler, & Jüttner, 2011).

Usually, it is assumed that crowding only deteriorates target identification but not target detection (Levi et al., 2002; Pelli et al., 2004; but see Allard & Cavanagh, 2011). However, omission errors under crowding are akin to a deterioration of detection: although the studies that revealed omission errors did not use standard detection tasks in which observers indicate target absence and presence, omission errors can be classified as failures of detection as the presence of an element (or a subset of elements) is not reported, similar to a miss in detection tasks. Whether omission errors are an integral (and often overlooked) characteristic of crowding is still unclear.

A particularly strong case of omission errors occurred when all displayed items were the same. For example, when presented with three closely-spaced Ts in the periphery (Figure 1), most participants verbally reported and drew only two Ts (Sayim & Taylor, 2019; see also Taylor & Sayim, 2018). Similarly, when subjects were asked to report all items of a letter trigram, many errors indicated the loss of a repeated letter feature (Coates, Bernard & Chung, 2019). We termed this phenomenon when one (or multiple) of a number of identical items is not reported "redundancy masking" (Sayim & Taylor, 2019; Yildirim, Coates, & Sayim, 2019a; see also Coates et al., 2019). Here, to characterize redundancy masking and to elucidate its relations and commonalities with crowding, we investigated the dependence of redundancy masking on spatial features. In particular, we investigated stimulus attributes that have been shown to be effective—or ineffective—in modulating crowding: spacing, spatial arrangement (anisotropy), size, and regularity.

One of the key characteristics of crowding is its dependence on the spacing between the target and the flankers (Bouma, 1970; Pelli et al., 2004): identification improves with increasing target-flanker spacing (Bouma, 1970; Pelli et al., 2004). The distance at which flankers cease to interfere with target identification, the critical spacing, is proportional to the target's eccentricity, and is often estimated to be approximately 0.5 times the eccentricity (in the radial direction, Bouma's law; Bouma, 1970, Pelli et al., 2004). However, the "crowding zone" in which flankers impair performance is anisotropic (Greenwood, Szinte, Sayim, & Cavanagh, 2017; Petrov & Popple, 2007; Toet & Levi, 1992). Flankers positioned along an axis directed to the fovea, that is, radial flankers, usually impair performance over larger distances than flankers that are positioned on the tangential axis (radial-tangential anisotropy; Chambers & Wolford, 1983; Pelli, Tillman, Freeman, Su, Berger, & Majaj, 2007; Toet & Levi, 1992).

A number of studies showed size invariance of crowding (Levi et al., 2002; Pelli et al., 2004; Strasburger et al., 1991; Tripathy & Cavanagh, 2002): the strength of crowding was determined primarily by the center-to-center spacing between target and flankers, not the distance between closest edges (the edge-to-edge spacing). For example, when presenting stimuli with different sizes (while keeping the target visibility constant), a five-fold increase in target size resulted in less than a 15% change in the spatial extent of crowding (Tripathy & Cavanagh, 2002). Hence stimulus size seems to be negligible in crowding. However, size differences of the target and the flankers do play a role in crowding, for example, because of a reduction of target-flanker similarity and target-flanker grouping (Levi & Carney, 2009; Malania et al., 2007; Manassi et al., 2012; Saarela et al., 2009; but see Pelli et al., 2004).

The strength of grouping between the target and the flankers is generally a good predictor of crowding strength, with strong (weak) target-flanker grouping yielding low (high) performance (Banks et al., 1979; Banks & White, 1984; Herzog, Sayim, Chicherov, & Manassi, 2015; Livne & Sagi, 2007; Manassi et al., 2012; Manassi et al., 2013; Saarela et al., 2009;

Sayim et al., 2010; Sayim et al., 2011; Wolford & Chambers, 1983). For example, when the spacing between all items—the target and multiple flankers—was the same (regular spacing), crowding and grouping were strong (Saarela, Westheimer, & Herzog, 2010). When the spacing was irregular, the target did not group with the flankers, and performance improved compared with regular spacing (Saarela et al., 2010). As performance depends on target-flanker grouping, the effect of regularity can be reversed when irregular arrangements of flankers group more strongly with the target than regular arrangements (Manassi et al., 2012; Sayim, Manassi, & Herzog, 2010). Although strong target-flanker grouping is usually associated with strong crowding, a number of recent studies showed that strong grouping can also be beneficial, for example, when the target groups with an identical shape presented in the fovea (Sayim, Greenwood, & Cavanagh, 2014) or when emergent features help to identify the target (Melnik et al., 2018, 2020). Importantly, although crowding and grouping share many features, such as the integration of information across space and their dependence on spacing and similarity, they are different processes as shown, for example, by their different spatial extents (Sayim & Cavanagh, 2013).

Note that these characteristics of crowding have typically been measured with flanked target identification. However, the deleterious effect of redundancy masking is easily missed when identifying a single target. For example, using a free report and drawing paradigm with displays such as in Figure 1, most observers reported only two letters, but they correctly reported the target as a “T” when asked to identify the central letter (Sayim & Taylor, 2019). Therefore to explicitly determine when a repeated item is lost, we used an enumeration task in which all items in the display were relevant. Previous enumeration experiments showed that accuracy is usually high up to approximately five presented items (Bourdon, 1908; Jensen, Reese, & Reese, 1950; Jevons, 1871; Kaufman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982; Piazza, Fumarola, Chinello, & Melcher, 2011; Revkin, Piazza, Izard, Cohen, & Dehaene, 2008; Taves, 1941; Trick & Pylyshyn, 1994). This so-called *subitizing* when small numbers of items are presented is different than the process for larger numbers in which the number of items is not easily “seen” but needs to be (imprecisely) estimated or deliberately counted (Jensen et al., 1950; Kaufman et al., 1949; Mandler & Shebo, 1982; Revkin et al., 2008; Trick & Pylyshyn, 1994). For example, in some of the earliest contributions, it was shown that enumeration errors start to emerge at four (Jurin, 1738; see also Strasburger & Wade, 2015) or five items (Jevons, 1871). Similarly, response times were shown to be almost invariant in enumeration tasks with arrays of up to approximately four items, followed by a rapid increase with increasing numbers of items (Jensen et al., 1950; Kaufman et al., 1949; Mandler & Shebo, 1982). Few studies have investigated subitizing in peripheral vision (Chakravarthi & Herbert, 2019; Palomares, Smith, Pitts, & Carter, 2011; Parth & Rentschler, 1984; Railo, Koivisto, Revonsuo, & Hannula, 2008). Here we used an enumeration task with relatively small numbers of items presented in the visual periphery to investigate redundancy masking.

In four experiments, observers were presented with arrays of small numbers of closely-spaced lines centered at 10° eccentricity in the left or right visual field. We varied the number of lines to obtain sufficient uncertainty, which is required to reveal the effect of redundancy masking (see General discussion; cf., Sayim & Taylor, 2019). The task was to indicate the number of lines. In Experiment 1, we investigated the role of spacing in redundancy masking by varying the distance between adjacent vertical lines. Redundancy masking was strong with small spacings, weakened with increasing spacing, and ceased at large spacings, showing that spacing strongly modulated redundancy masking. In Experiment 2, we investigated the effect of spatial arrangement by presenting radial (horizontally arranged vertical lines as in Experiment 1) and tangential (vertically arranged horizontal lines) arrays of lines. We found strong redundancy masking with radial arrangements and no redundancy masking with tangential arrangements of lines. In Experiment 3, we asked whether target size modulates redundancy masking, varying line length and width. The strength of redundancy masking was independent of the length of the lines; however, it was modulated by the width of the lines, yielding less redundancy masking with thicker compared with thinner lines. Finally, in Experiment 4 we varied the regularity of the line arrays by introducing vertical or horizontal jitter to individual lines. We found that regularity influenced the strength of redundancy masking. High regularity of the line arrays resulted in strong redundancy masking, and a reduction of regularity decreased redundancy masking in conditions with small numbers of lines. Taken together, we revealed several key characteristics of redundancy masking by showing how spacing, spatial arrangement, size, and regularity modulated the perception of peripherally presented arrays of lines.

Experiment 1: Spacing

In all experiments, observers were presented with three to seven lines (three to six in Experiment 1) in the peripheral visual field and were asked to indicate the number of lines.

In Experiment 1, we varied the spacing between adjacent lines to investigate the dependence of redundancy masking on spacing. We hypothesized that redundancy masking would decrease with increasing spacing between elements.

Methods

Participants

Five undergraduate students (age range 20–25, one male) from the University of Bern participated in the experiment in exchange for course credit. All observers reported normal or corrected-to-normal visual acuity. Participants were naive regarding the aim of the study. Before the experiment, participants signed a consent form and were informed about the general procedure. The experimental protocols were approved by the local ethics committee at the University of Bern. All procedures were in accordance with the Declaration of Helsinki.

Apparatus and stimuli

Stimuli were generated with Psychopy v2.7.11 (Peirce, 2007) and displayed on a 21-in. CRT monitor with a resolution of 1024 × 768 and refresh rate of 75 Hz. The experiment was conducted in a dimly illuminated room. Observers viewed the monitor from a distance of 57 cm and were supported by a chin and head rest. A black fixation disc (diameter = 12′; 2 cd/m^2) was presented at the center of the screen throughout the experiment. Stimuli consisted of black (2 cd/m^2) lines that were 65.8′ in length and 2.3′ in width, presented on a uniform gray background (80 cd/m^2). The line array was centered at 10° eccentricity to either the right or the left of the fixation disc. The number of presented lines ranged from three to six. The center-to-center spacing between adjacent lines (inter-line spacing) within a line array was identical but varied randomly across trials. In trials with three or four lines, the inter-line spacings ranged from 46.5′ to 186.1′ in steps of 34.9′ (46.5′, 81.4′, 116.3′, 151.2′, and 186.1′). Smaller maximal spacings were used for trials with five and six lines, with adjacent lines separated by 46.5′, 69.8′, 81.4′, 93′, or 104.7′ to avoid exceeding limitations of screen size. The position of the line array was slightly varied at random across trials (centered at 10° or jittered 4.7′ either up, down, left, or right). Responses were recorded using a number pad. Example stimuli featuring different spacings are illustrated in Figure 2a.

Task and procedure

At the beginning of the experiment, the fixation disc was presented for 1s. Next, a stimulus was presented for 150 ms to the left or the right of fixation. Observers were required to indicate the number of lines they perceived with a key press on the number pad (0–9). The next stimulus was presented 440 ms after each response. The stimulus location (left or right of

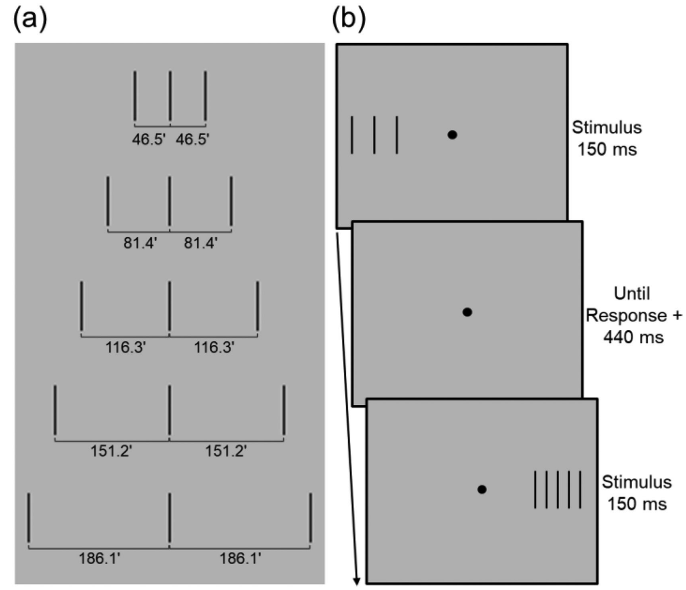

Figure 2. (a) Illustration of the stimuli used in Experiment 1. Line triplets with the five inter-line spacings are shown. (b) Schematic depiction of the procedure. (Stimuli are not drawn to scale).

fixation), the number of lines (three to six), and the eight different inter-line spacings were randomized and counterbalanced within each block. In each block there were 240 trials. Observers completed 2 blocks (a total of 480 trials). A schematic depiction of the procedure is shown in Figure 2b.

Before the experiment, for each participant we verified that the spacing between adjacent lines was above their resolution limit. A two-line discrimination task with 140 trials was performed before the main experiment: two lines with varying spacings were presented at the farthest eccentricity of the main experiment (14.7°). Participants were asked whether they perceived one or two lines. All observers perceived two lines in 100% of the trials in the smallest inter-line spacing presented in the main experiment (46.5′).

Data analyses

Performance was defined as the number of lines presented subtracted from the number of lines reported ("deviation"). Hence if the number of lines reported was the same as the number of lines presented, the deviation was zero; reporting more lines than presented yielded deviation scores above zero, and reporting fewer lines than presented yielded deviation scores below zero. In all experiments, deviation scores were analyzed by linear mixed-effects models specifying subject as a random factor, and experimental manipulations (spacing in Experiment 1, spatial arrangement in Experiment 2, line width and line length in Experiment 3, and spatial regularity in

Experiment 4) and the number of lines presented as fixed effects. Analyses were carried out with R (R Core Team, 2018), using the lmer function of the lme4 package (Bates, Mächler, Bolker, & Walker, 2014). For model selection, null (without any fixed effects), reduced (experimental manipulation as the fixed effect), and full (the number of lines presented and experimental manipulation as the fixed effects) models were fitted and hierarchically compared. Similar incremental model building was used to select the minimum degree polynomial that fitted the data. Likelihood-ratio tests with Satterthwaite's approximation for degrees of freedom were performed for model comparisons, and the Akaike information criterion was used to select the best fitting model (Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017; plotted with the ggplot2 package, Wickham, 2009). Confidence intervals were calculated with the ggpredict function of the ggeffects package (Lüdecke, 2018). Effect sizes for the fixed effects were evaluated using semipartial R squared (r^2), which represents the strength of association between the dependent variable (deviation scores) and the fixed effect, controlling for the other effects in the model (Jaeger, 2016; Jaeger, Edwards, Das, & Sen, 2017). The model R squared statistic (R^2) was computed to quantify goodness-of-fit. Assumptions underlying the models were checked with diagnostic plots of residuals (Cohen, Cohen, West, & Aiken, 2003; Pinheiro & Bates, 2000). The Shapiro–Wilk tests were used to test for deviations from normality in the residuals.

Results

Figure 3 shows the deviation scores for Experiment 1 as a function of spacing for all numbers of lines presented. A third-degree polynomial regression was used to fit the data. The fixed effects were the number of lines presented (three to six) and spacing (46.5′–186.1′). The random effects structure contained random intercepts for each subject. The likelihood ratio tests showed that the reduced model was better than the null model, indicating that deviation scores depended on spacing ($R^2 = 0.36$: Supplementary Table S1, Experiment 1). The comparison between the full model and the reduced model showed that the inclusion of the number of lines presented did not have a significant effect on the model (Supplementary Table S1, Experiment 1). Hence we used the reduced model with the effect of spacing (Figure 3). The coefficients for the reduced model are shown in the Supplementary Table S2 (Experiment 1).

The results indicate that spacing had a pronounced effect on redundancy masking: redundancy masking was stronger for smaller compared with larger spacings. When the inter-line spacing was small (46.5′–81.4′), the average deviation scores were clearly below zero for all numbers of lines presented and varied only slightly among the spacings (Figure 3). Deviation scores approached zero with increasing spacing, and there was no evidence for redundancy masking at larger spacings (151.2′ and 186.1′). Overall, the results revealed a clear dependence of redundancy masking on spacing.

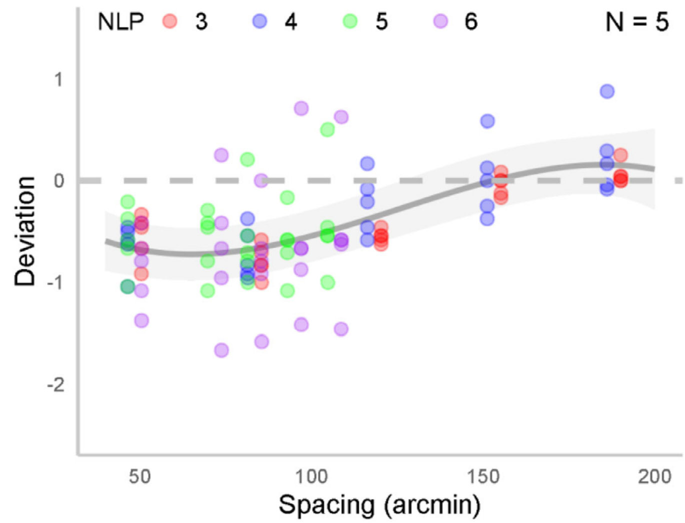

Figure 3. Results of Experiment 1. Red (three lines), blue (four lines), green (five lines), and purple (six lines) data points show mean deviation scores for each individual observer. A third-degree polynomial regression was used to fit the data. Shaded regions represent confidence intervals based on the standard errors (±1.96 * *SE*). (Notes: Data points are slightly offset for clarity, NLP: The number of lines presented).

Experiment 2: Radial-tangential anisotropy

Experiment 1 showed that redundancy masking depended on spacing: at large spacings, redundancy masking ceased. In crowding, not only the distance between the flankers and the target but also where the flankers are placed with regard to the target is important. In Experiment 2, we thus investigated whether redundancy masking differed for radial (horizontally arranged vertical lines) and tangential (vertically arranged horizontal lines) arrangements of lines (Figure 4). We expected stronger redundancy masking with radially compared with tangentially arranged lines.

Methods

Participants

Eight students (age range 20–23, one male) participated in the experiment in exchange for course credit or payment.

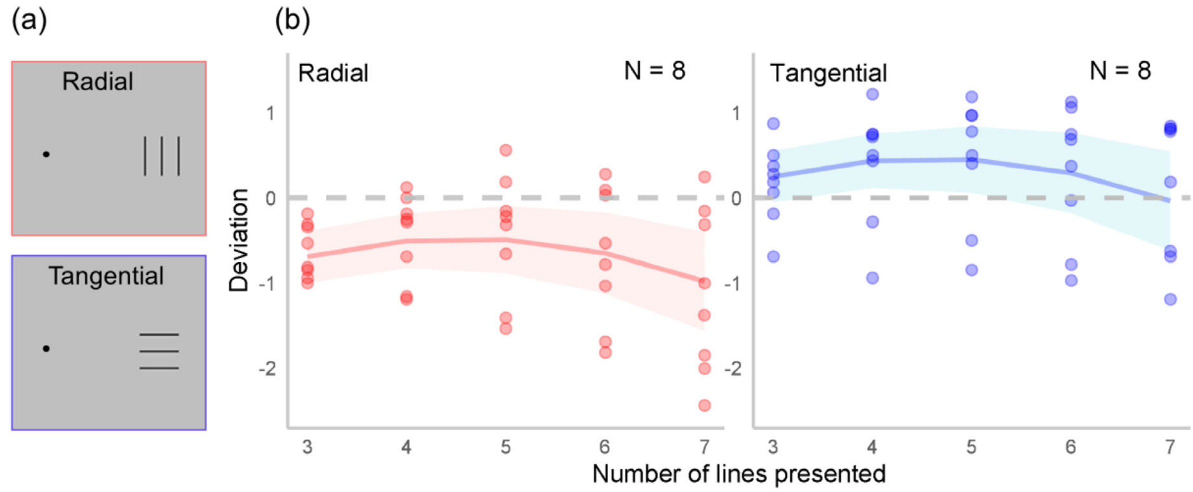

Figure 4. Illustration of the stimuli (a) and results (b) of Experiment 2. (a) Line triplets for radial (top) and tangential (bottom) arrangements are shown. (b) Red (radial) and blue (tangential) data points show mean deviation scores for each individual observer. A second-degree polynomial regression was used to fit the data. Shaded regions represent confidence intervals based on the standard errors (± 1.96 * *SE*).

Apparatus and stimuli

Stimuli were displayed on a 22-in. CRT monitor with a refresh rate of 110 Hz and a resolution of 1152 × 864. Stimuli were the same as in Experiment 1 except for the following differences. The luminance values of the lines and the background were 1 and 42 cd/m^2, respectively. Lines were 60′ in length and 2.1′ in width, in both the radial and tangential condition. The number of lines presented ranged from three to seven. The center-to-center spacing between adjacent lines was fixed at 25.4′. There were two conditions: in the radial condition, vertically oriented lines were horizontally arranged (Figure 4a, top), and in the tangential condition, horizontally oriented lines were vertically arranged (Figure 4a, bottom). The conditions are denoted as radial and tangential to refer how the lines are located relative to fixation. Note that not only the arrangement of lines but also their orientation was different in the radial and tangential conditions.

Task and procedure

The task and procedure were the same as in Experiment 1 except for the following differences. Presentations were blocked according to the spatial arrangement of lines (radial and tangential). A block consisted of 80 trials. Observers completed two blocks with each spatial arrangement (a total of 320 trials). The sequence of radial and tangential blocks was pseudorandomized for each observer.

As in Experiment 1, a two-line discrimination task with 100 trials was performed with radial and tangential lines before the main experiment (a total of 200 trials). The lines were presented on the horizontal meridian at the maximum eccentricity of lines in the main experiment (radial: 11.3°, tangential: 10°). All observers perceived two lines in at least 95% of the trials in the smallest inter-line spacing presented in the main experiment (25.4′).

Results

Deviation scores for radially and tangentially arranged lines are shown as a function of the number of lines presented in Figure 4b. A second-degree polynomial regression was used to model the data. The fixed effects were the number of lines presented (three to seven) and spatial arrangement of the lines (radial and tangential). The random effects structure contained random slopes and random intercepts for each subject. Results showed that the reduced model was better than the null model, and the full model was better than the reduced model (Supplementary Table S1, Experiment 2). Hence the full model was selected (Figure 4b). Spatial arrangement had a strong effect on deviation scores ($R^2 = 0.36$: Supplementary Table S1, Experiment 2; $r^2_{tangential} = 0.34$: Supplementary Table S2, Experiment 2). The coefficients for the full model are shown in the Supplementary Table S2 (Experiment 2). The average deviation scores were clearly below zero in the radial condition (–0.66 ± *SD* 0.58), and they were above zero in the tangential condition (0.28 ± *SD* 0.65). The number of lines reported varied with the number of lines presented in a quadratic (inverted-U) manner for both the radial and the tangential conditions (as

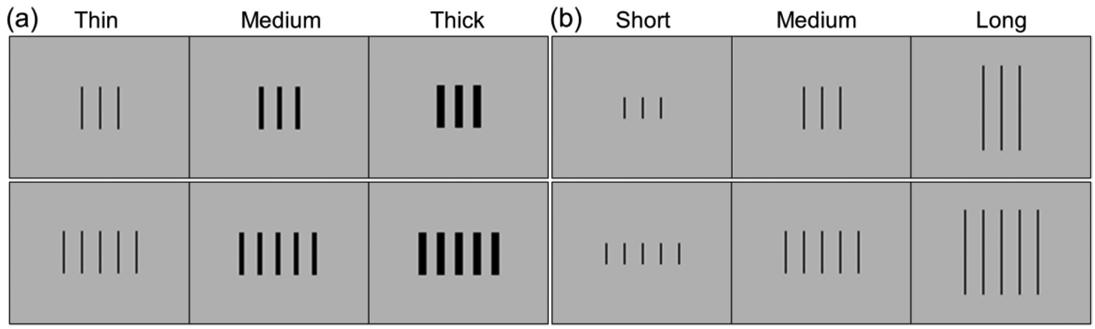

Figure 5. Illustration of the stimuli used in Experiment 3. Line triplets (top row) and quintuplets (bottom row) for (a) Experiment 3a (width) and (b) Experiment 3b (length) are shown.

confirmed by the linear mixed-effects analysis). In both conditions, an initial positive slope of the deviation scores for small numbers of lines presented was followed by a negative slope with larger numbers of lines. Both functions reached their maximum at five lines in which they differed by 0.88 (–0.44 in the radial and 0.43 in the tangential condition; Figure 4b).

Overall, the perceived number of lines was lower in the radial compared with the tangential condition. In contrast to the radial condition, observers reported more lines than were presented in the tangential condition. Hence the results show a clear radial-tangential asymmetry: there was strong redundancy masking in the radial condition and the opposite effect (overestimation) in the tangential condition.

Experiment 3: Size

In Experiment 3, we examined whether the strength of redundancy masking depended on target size. As crowding tends to be immune to changes in target size, there should be little or no effect of target size on redundancy masking if it resembled crowding in this regard. We varied the width (Experiment 3a) and length (Experiment 3b) of the lines. As redundancy masking was strongest with small spacings (Experiment 1), and only occurred with radially but not tangentially arranged lines (Experiment 2), we used small spacings and radially arranged lines in Experiment 3.

Methods

Experiment 3a: Line width

Participants: Eight students (age range 19–23, all female), including two of the observers from Experiment 2, participated in the experiment in exchange for course credit.

Apparatus and stimuli: Apparatus and stimuli were the same as in Experiment 2 except for the following differences. Only radially arranged vertical lines were used. The width of the lines was varied: thin (2.1′), medium (6.4′), or thick (10.6′). The edge-to-edge spacing between lines for the thin, medium, and thick conditions was 23.3′, 19′, and 14.8′, respectively. The center-to-center spacing was again 25.4′. Figure 5a illustrates example stimuli (line triplets and quintuplets).

Task and procedure: The task and procedure were the same as in Experiment 2 except that presentations were blocked according to the width of the lines (thin, medium, and thick). Observers completed two blocks of 80 trials with each width (a total of 480 trials). The sequence of thin, medium, and thick blocks was pseudorandomized for each observer.

Before the main experiment, the same two-line discrimination task with 100 trials described in the previous experiments was performed with thin and thick lines (a total of 200 trials). The lines were presented at 11.3° eccentricity. All observers perceived two lines in at least 95% of the trials with the smallest inter-line spacing presented in the main experiment (25.4′).

Results

Results of Experiment 3a are shown in Figure 6. A second-degree polynomial regression was used to model the data. The fixed effects were the number of lines presented (three to seven) and line width (thin, medium, and thick). The random effects structure contained random slopes and random intercepts for each subject. The comparisons between models showed that the reduced model was better than the null model, and the full model was better than the reduced model, indicating a significant effect of line width, although with a small effect size ($R^2 = 0.14$: Supplementary Table S1, Experiment 3a; $r^2_{medium} = 0.05$ and $r^2_{thick} = 0.02$: Supplementary Table S2, Experiment 3a). The

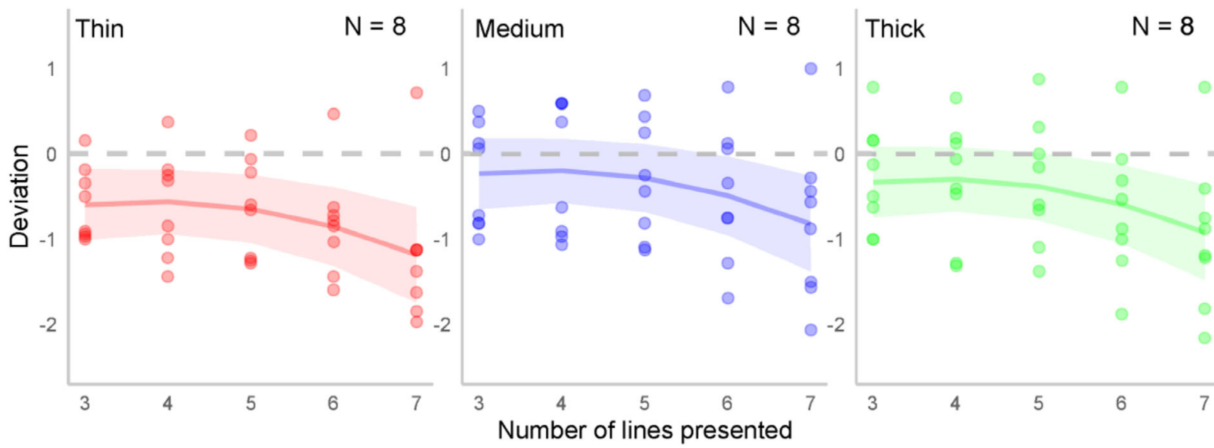

Figure 6. Results of Experiment 3a. Red (thin lines), blue (medium lines), and green (thick lines) data points show mean deviation scores for each individual observer. A second-degree polynomial regression was used to fit the data. Shaded regions represent confidence intervals based on the standard errors (± 1.96 * *SE*).

full model was selected (Figure 6). The coefficients for the full model are shown in the Supplementary Table S2 (Experiment 3a). The number of lines reported was lower than the number of lines presented with thin lines (average deviation scores: –0.77 ± *SD* 0.51). Compared with thin lines, the number of lines reported was increased by 0.36 ± *SE* 0.06 for medium and 0.26 ± *SE* 0.06 for thick lines. The fitted curves show a quadratic decrease of the number of lines reported with increasing number of lines presented (Figure 6).

Overall, the results indicate that redundancy masking depended to some extent on the width of the lines: the number of lines perceived was smaller with thin compared with medium and thick lines. But small effect sizes and overall negative deviation scores (thin lines: −0.77 ± *SD* 0.51; medium lines: –0.40 ± *SD* 0.69; thick lines: –0.50 ± *SD* 0.68) indicate that the number of lines reported was consistently lower than the number of lines presented regardless of the width of the lines.

Methods

Experiment 3b: Line length

Participants: Five students (age range 21–29, one male), including four of the observers from Experiment 3a, participated in the experiment in exchange for course credit.

Apparatus and stimuli: Apparatus and the stimuli were the same as in Experiment 3a but only using thin lines (2.1′). The length of the lines was varied: short (30′), medium (60′), or long (120′). Figure 5b illustrates example stimuli (line triplets and quintuplets).

Task and procedure: The task and procedure were the same as in Experiment 3a except that presentations were blocked according to line length (short, medium, and long).

Before the main experiment, the same two-line discrimination task with 100 trials as in the other experiments was performed with short and long lines (a total of 200 trials). All participants reported two lines in at least 95% of the trials with the smallest inter-line spacing presented in the main experiment (25.4′).

Results

Results for Experiment 3b are shown in Figure 7. A second-degree polynomial regression was used to model the data. The fixed effects were the number of lines presented (three to seven) and line length (short, medium, and long). The random effects structure contained random intercepts for each subject. The comparisons between the models showed that the reduced model was not different from the null model, indicating that there was no effect of line length on deviations scores ($R^2 = 0.01$: Supplementary Table S1, Experiment 3b). Because line length did not yield a significant change, the model with the fixed effect of the number of lines presented was used (Figure 7). The coefficients for this model are shown in the Supplementary Table S2 (Experiment 3b). As in Experiment 3a, the fitted curves indicate a quadratic decrease of the number of reported lines with increasing numbers of presented lines.

As evidenced by the small effect size for line length and overall negative deviation scores (short lines: –0.92 ± *SD* 0.40; medium lines: –0.96 ± *SD* 0.44; long lines: –0.83 ± *SD* 0.58), redundancy masking was strong with all tested line lengths, suggesting that length did not play a role for the strength of redundancy masking (at least for the range of lengths tested here).

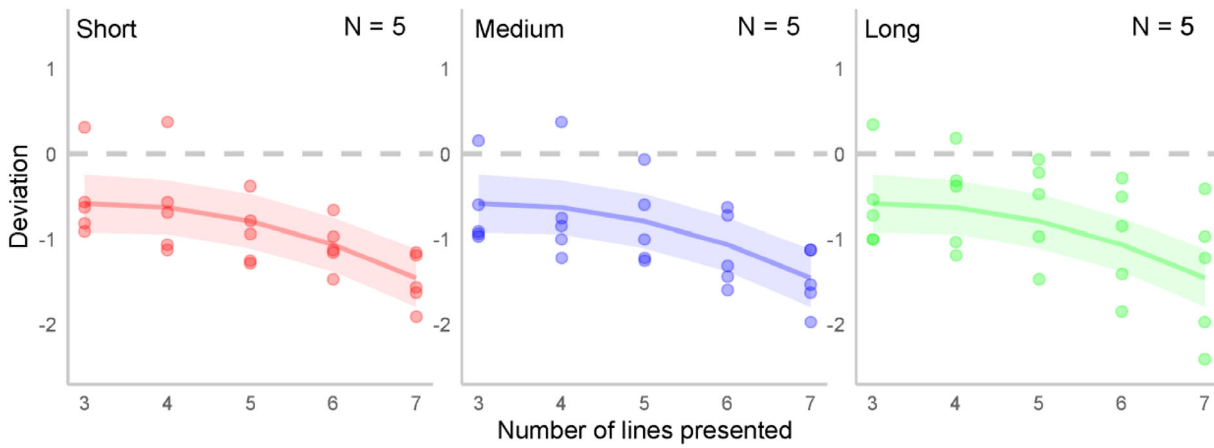

Figure 7. Results of Experiment 3b. Red (short lines), blue (medium lines), and green (long lines) data points show mean deviation scores for each individual observer. A second-degree polynomial regression was used to fit the data. Shaded regions represent confidence intervals based on the standard errors (± 1.96 * *SE*).

Experiment 4: Regularity

In Experiment 4, we examined whether redundancy masking was affected by spacing regularity. The preceding experiments showed similar dependencies of redundancy masking on factors that influence crowding, and a divergent effect of size (line width). As the strength of crowding is modulated by spacing regularity, we expected that redundancy masking would depend on spacing regularity as well. Here we varied the regularity of the line arrays by introducing horizontal (Experiment 4a) and vertical (Experiment 4b) jitter.

Methods

Experiment 4a: Horizontal jitter

Participants: Seven students (age range 20–24, one male) participated in the experiment in exchange for course credit or payment.

Apparatus and stimuli: Apparatus and the stimuli were the same as in Experiment 2 but only using radially arranged vertical lines. There were three conditions: regular, weak jitter, and strong jitter. In the regular condition, the distance between adjacent lines was identical (50.9′). In the other two conditions, horizontal jitter was introduced. In both jitter conditions, the outermost two lines remained at the same positions as the two outermost lines in the regular condition. The remaining lines were each jittered randomly to either the left or right by 8.5′ (weak jitter) or 17′ (strong jitter) in separate blocks. In the weak jitter condition, the smallest and widest spacings between adjacent lines were 33.9′ and 67.8′, respectively. In the strong jitter condition, the smallest and widest spacings between adjacent lines were 17′ and 84.8′, respectively. In both conditions, jittering did not cause any overlap between line positions. In Figures 8a and 8b, example stimuli (line triplets and quintuplets) for each condition are illustrated.

Task and procedure: The task and procedure were the same as in Experiment 2 except that presentations were blocked according to jitter condition (regular, weak jitter, and strong jitter). A block consisted of 90 trials. Observers completed two blocks with each jitter condition (a total of 540 trials). The sequence of the regular, weak jitter, and strong jitter blocks was pseudorandomized for each observer.

Before the main experiment, the same two-line discrimination task with 100 trials described earlier was performed at 12.6°, and 11.5° eccentricities (a total of 200 trials). Because the closest inter-line spacings were 33.9′ at 12.6°, and 17′ at 11.5°, these eccentricities were chosen for stimulus presentation. All participants perceived two lines in at least 95% of the trials, with the smallest inter-line spacings presented in the main experiment (33.9′ and 17′).

Results

Results of Experiment 4a are shown in Figure 9. A second-degree polynomial regression was used to fit the deviation scores on the number of lines presented. The fixed effects contained the number of lines presented (three to seven) and jitter condition (regular, weak jitter, and strong jitter). The random effects structure contained random slopes and random intercepts for each subject. All model comparisons yielded significant results ($R^2 = 0.28$: Supplementary Table S1, Experiment 4a; $r^2_{\text{weak jitter}} = 0.0006$ and

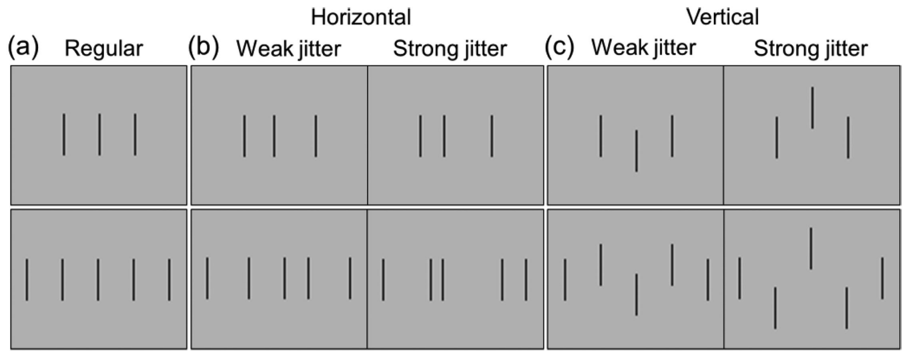

Figure 8. Illustration of the stimuli used in Experiment 4. Line triplets (top row) and quintuplets (bottom row) for Experiment 4a (regular (a) and horizontal jitter (b)) and Experiment 4b (regular (a) and vertical jitter (c)) are shown.

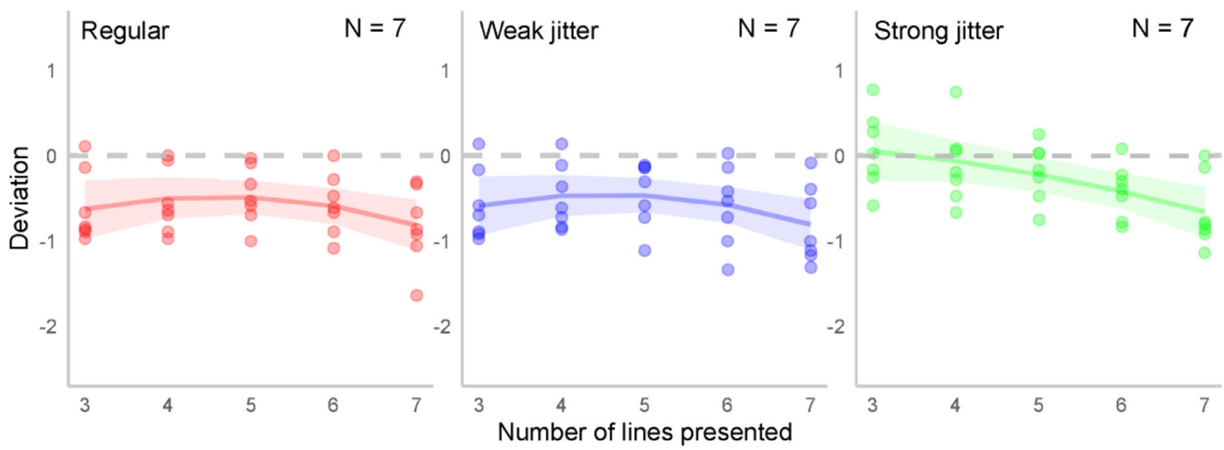

Figure 9. Results of Experiment 4a. Red (regular), blue (weak jitter), and green (strong jitter) data points show mean deviation scores for each individual observer. A second-degree polynomial regression was used to fit the data. Shaded regions represent confidence intervals based on the standard errors (± 1.96 * *SE*).

$r^2_{\text{strong jitter}} = 0.12$: Supplementary Table S2, Experiment 4a). Thus the full model with interaction was selected (Figure 9). The coefficients for the full model are shown in the Supplementary Table S2 (Experiment 4a). The average deviation scores were negative in all three conditions. In the strong jitter condition, the number of lines reported was lower compared with the other two conditions (regular: –0.60 ± *SD* 0.30; weak jitter: –0.58 ± *SD* 0.32; strong jitter: –0.26 ± *SD* 0.27). The fitted curves show the interaction between number of lines presented and jitter condition. In the regular and weak jitter conditions, a quadratic relationship was observed between the deviation scores and the number of lines presented (the number of lines reported increased to a maximum at five lines, then decreased), whereas in the strong jitter condition, a linear relationship was observed (the number of lines reported decreased linearly with increasing number of lines presented).

In the regular condition, the deviation scores were clearly below zero for small numbers of lines presented (three lines: –0.61 ± *SD* 0.42; four lines: –0.54 ± *SD* 0.38), whereas in the strong jitter condition they were close to zero (three lines: 0.07 ± *SD* 0.45; four lines: –0.10 ± *SD* 0.46). In contrast, for six and seven lines, the deviation scores minimally varied between the regular (six lines: –0.57 ± *SD* 0.36; seven lines: –0.83 ± *SD* 0.46) and the strong jitter conditions (six lines: –0.42 ± *SD* 0.32; seven lines: –0.66 ± *SD* 0.42). To summarize, redundancy masking was pronounced in the regular and weak jitter conditions and weak in the strong jitter condition. With three and four lines, deviation scores were close to zero in the strong jitter condition, indicating that strong jitter prevented redundancy masking when the number of lines presented was small.

Methods

Experiment 4b: Vertical jitter

Participants: Seven students (age range 20–24, all female) participated in the experiment in exchange for course credit.

Apparatus and stimuli: The apparatus was the same as in Experiment 4a. In Experiment 4b, we used vertical instead of horizontal jitter. In all conditions, the horizontal distance between adjacent lines was

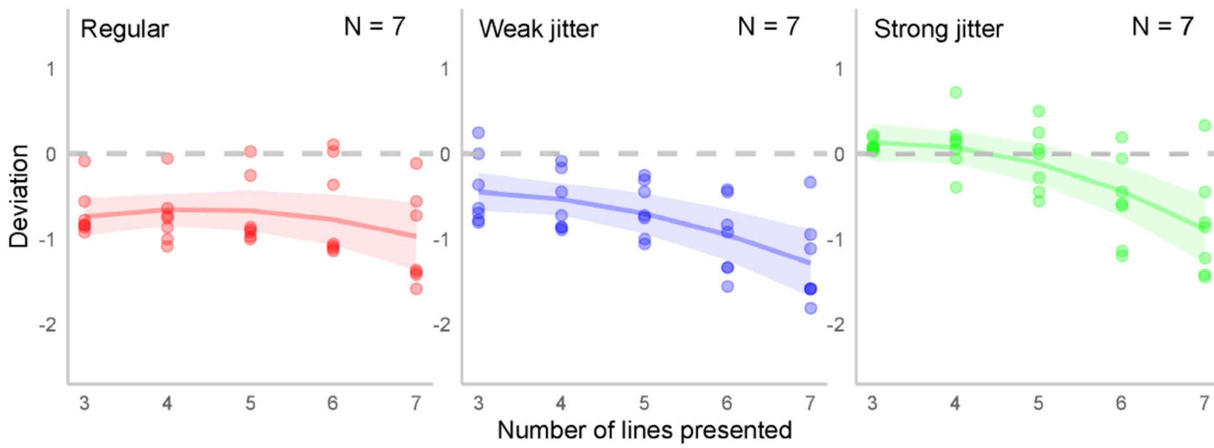

Figure 10. Results of Experiment 4b. Red (regular), blue (weak jitter), and green (strong jitter) data points show mean deviation scores for each individual observer. A second-degree polynomial regression was used to fit the data. Shaded regions represent confidence intervals based on the standard errors (± 1.96 * *SE*).

identical (50.9′). The regular condition was the same as in Experiment 4a. In the two jitter conditions, the outermost two lines were not jittered and remained at the same positions as the two lines in the regular condition. The remaining lines were randomly jittered up or down by 21.2′ (weak jitter) or 42.4′ (strong jitter) in separate blocks. Thus, the overlap between the fixed (outermost) and jittered lines was 65% and 29% in the weak and strong jitter conditions, respectively (100% in the regular condition). In Figures 8a and 8c, example stimuli (line triplets and quintuplets) for each condition are shown.

Task and procedure: The task and procedure were the same as in Experiment 4a.

The same two-line discrimination task with 100 trials was performed before the main experiment. The lines were presented at 12.6°. All participants perceived two lines in at least 95% of the trials in the smallest inter-line spacing presented in the main experiment (50.9′).

Results

Results of Experiment 4b are shown in Figure 10. A second-degree polynomial regression was used to fit the deviation scores on the number of lines presented. The fixed and random effects were the same as in Experiment 4a. All comparisons yielded significant results ($R^2 = 0.47$: Supplementary Table S1, Experiment 4b; $r^2_{\text{weak jitter}} = 0.0005$ and $r^2_{\text{strong jitter}} = 0.22$: Supplementary Table S2, Experiment 4b). Thus the full model with interaction was selected (Figure 10). The coefficients for the full model are shown in the Supplementary Table S2 (Experiment 4b). The average deviation scores were negative for all conditions, but the number of lines reported was higher in the strong jitter condition compared with the other two conditions (regular: –0.76 ± *SD* 0.38; weak jitter: –0.78 ± *SD* 0.31; strong jitter: –0.25 ± *SD* 0.36). The number of lines reported was increased by 0.51 ± *SE* 0.05 in the strong jitter condition in comparison to the regular condition. The data indicate that there was an interaction between jitter condition and the number of lines presented. Although the slope in the regular condition was relatively flat, there was a marked increase of redundancy masking from small to large numbers of lines in the two jitter conditions.

In comparison to the regular condition (three lines: –0.69 ± *SD* 0.29; four lines: –0.73 ± *SD* 0.34; five lines: –0.69 ± *SD* 0.41), deviation scores were close to zero in the strong jitter condition (three lines: 0.10 ± *SD* 0.07; four lines: 0.12 ± *SD* 0.33; five lines: –0.07 ± *SD* 0.38) for small numbers of lines presented. In contrast, for six and seven lines, the deviation scores varied only minimally between the regular (six lines: –0.66 ± *SD* 0.57; seven lines: –1.02 ± *SD* 0.56) and the strong jitter conditions (six lines: –0.55 ± *SD* 0.51; seven lines: –0.84 ± *SD* 0.63): Observers underestimated the number of lines in the majority of the trials in both conditions for six and seven lines. To sum up, redundancy masking was strong in the regular and weak jitter conditions, and weak in the strong jitter condition. Strong vertical jitter decreased redundancy masking especially for small numbers of lines.

General discussion

In four experiments, we revealed several characteristics of redundancy masking. First, redundancy masking strongly depended on the spacing between elements. Larger spacing yielded weaker redundancy masking than smaller spacing. Second, we found a pronounced radial-tangential anisotropy. When radially arranged lines were presented, redundancy masking was strong. Tangentially arranged lines yielded an overestimation of the number of lines instead of redundancy masking. Third, to a certain extent there was an effect of size on redundancy masking. While our variations of line length did not result in any reduction of redundancy masking, thicker lines decreased redundancy masking compared with thinner lines. Fourth, regularity played an important role. Regularly spaced line arrays resulted in strong redundancy masking, whereas irregular spacings did not yield redundancy masking (at least for small numbers of lines).

A pronounced dependence on spacing, one of the hallmarks of crowding, was found in Experiment 1. When the spacings were smaller than 104.7′ (1.75°, 0.17 × the eccentricity), redundancy masking was strong and showed little variation among the spacings. There was a reduction of redundancy masking with increasing inter-line spacing, and no redundancy masking with the largest tested spacings of 151.2′ (2.52°, 0.25 × the eccentricity) and 186.1′ (3.1°, 0.31 × the eccentricity). As the larger spacings in Experiment 1 were only tested with three and four but not with five and six lines, it is not certain whether redundancy masking would also cease when further increasing the spacing in these conditions. However, the deviation scores were highly similar for the spacings tested with all numbers of lines, and the data were fitted well with the same curve, suggesting that redundancy masking would also decrease with increasing spacing for five and six lines.

Redundancy masking occurred for inter-line spacings of approximately up to 0.19 × the eccentricity of the line array (116.3′). By contrast, flankers in crowding often affect performance over larger distances of up to 0.3 to 0.7 × the target eccentricity (Bouma, 1970; Pelli et al., 2004). Because our task and stimuli were different from those used in typical crowding studies, however, it was not expected that the same spatial extent as observed in crowding would also hold for redundancy masking. For example, in contrast to most crowding studies, in our paradigm, all presented items were task-relevant, which requires slightly more diffuse rather than focused attention (for diffuse vs. focused attention in crowding see Coates & Sayim, 2018; Petrov & Meleshkevich, 2011a). Moreover, also in crowding, the zone in which flankers interfere with target perception strongly depends on the stimuli and estimates of the size of the interference zone cannot easily be generalized (Herzog et al., 2015). For example, in Vernier discrimination, interference by flanking lines can be much smaller, with critical spacing estimates as small as 0.15 times the eccentricity (Levi et al., 1985) compared with, for example, letters in which crowding was reported to occur over distances of about 0.3 to 0.7 × the eccentricity (Bouma, 1970; Pelli et al., 2004; Strasburger et al., 1991; Toet & Levi, 1992). Overall, similar to crowding, spacing was shown to play a major role in redundancy masking.

In Experiment 1, the lines were arranged radially, and we found redundancy masking for all numbers of lines when the inter-line spacing was small. In Experiment 2, we tested whether redundancy masking was similar with tangentially arranged horizontal lines and radially arranged vertical lines. The pattern of results with radially arranged lines was the same as in Experiment 1: there was strong redundancy masking for all numbers of lines. However, when the lines were arranged tangentially, there was no redundancy masking for any number of lines. Instead, observers often reported more lines than were presented. Such categorically opposing effects (underestimation vs. overestimation) are rarely possible in crowding paradigms; for example, tangential flankers simply interfere less (and over a smaller spatial extent) with target identification than radial flankers. The reasons for this overestimation in the tangential condition are currently unclear. However, we can exclude that it was simply due to implicit or explicit comparisons with the underestimated stimuli in the radial condition because the two conditions were presented in different blocks, and there was no effect of the order of conditions. In contrast to the radial condition, in which redundancy masking was strong already with three lines, overestimation in the tangential condition was pronounced only with intermediate numbers of lines. Interestingly, the shape of both curves was highly similar, suggesting a similar dependence on the number of lines; however, with a remarkable difference of deviation scores by about one line. Taken together, our results revealed a clear radial-tangential anisotropy similar to crowding where flankers placed radially with respect to the fovea yield stronger impairment than flankers placed tangentially (Chambers & Wolford, 1983; Toet & Levi, 1992). Note that not only the arrangement of the lines but also their orientation differed in the radial and tangential conditions. Systematic variations of line orientation and stimulus location are needed to reveal whether redundancy masking depends on orientation, and whether the reported anisotropy holds for the entire visual field.

A number of studies have shown that the magnitude of crowding is independent of target and flanker size over a large range of sizes (Levi et al., 2002; Pelli et al., 2004; Strasburger et al., 1991; Tripathy & Cavanagh, 2002). In Experiment 3, we tested whether size modulated redundancy masking. We tested three different line widths (Experiment 3a) and found that redundancy masking was weaker with medium and thick lines compared with thin lines. Overall, these results suggest that line width influences redundancy masking. In Experiment 3b, we did not find any influence of line length on redundancy masking. The perceived number of lines was smaller than the number of lines presented regardless of the length of the lines, indicating that redundancy masking is independent of length, at least for the line lengths tested here. Results from a study (Sayim & Taylor, 2019) in which strong redundancy masking was observed for letters "T" (1.4 × 1.1° presented at 10° eccentricity) demonstrated that redundancy masking also occurs for larger, more spatially complex targets. Taken together, our results showed that redundancy masking occurred for a range of stimulus sizes. An increase of stimulus size can weaken redundancy masking but seems not to eliminate it completely.

High regularity has been shown to either increase (Manassi et al., 2012; Sayim, Manassi, & Herzog, 2010) or decrease (Saarela et al., 2010) performance on a single target in crowding depending on whether the target did or did not group with the flankers. Here all items were targets, excluding interpretations in terms of target-flanker grouping. Rather, the organization of the entire display and how it affects the perception of all lines needs to be considered. In Experiment 4, we found that high regularity yielded worse performance (stronger redundancy masking) than low regularity. Spacing regularity of the line arrays played a particularly strong role when the number of lines was small. Although slightly irregular spacings (weak jitter) did not reduce redundancy masking, highly irregular spacings by strong horizontal (Experiment 4a) and vertical (Experiment 4b) jitter abolished redundancy masking for up to five lines, possibly due to grouping the line arrays into distinct chunks. For example, when three lines were presented in the strong vertical jitter condition, the central line overlapped with the two outer lines by only 29% of its length, clearly separating it from the two outer lines. Similarly, the three lines in the strong horizontal jitter condition contained two lines in close proximity and a third line at a larger distance. These irregularities in both (strong vertical and horizontal jitter) conditions presumably facilitated the task and abolished redundancy masking because the stimulus could be parsed into a few (approximately two to three) separate and clearly different chunks containing one or two lines. The more lines were presented, the weaker was the expected benefit of grouping because the number of lines in the chunks would increase. In line with this prediction, our results showed no decrease of redundancy masking in the jitter conditions with larger numbers of lines.

We observed strong redundancy masking with small numbers of lines. This is in contrast to the usual finding that the enumeration of small numbers of items is highly accurate (Jensen et al., 1950; Kaufman et al., 1949; Piazza et al., 2011; Revkin et al., 2008; Trick & Pylyshyn, 1994). As humans usually do not have to estimate small numbers of items (approximately four) but "see" (or subitize) them without counting, the reduction of the reported number of items in redundancy masking is not simply due to estimation inaccuracies. Rather, we suggest that entire items are lost (or "masked") in redundancy masking. In contrast to most subitizing studies, which presented stimuli foveally and found accurate enumerations (Kaufman et al., 1949; Piazza et al., 2011; Revkin et al., 2008), our stimuli were presented in the near visual periphery. Only a few previous studies have investigated subitizing in the near visual periphery (10°: Chakravarthi & Herbert, 2019; 11°: Palomares et al., 2011; 4°, 8°, and 20°: Parth & Rentschler, 1984; 3.3°: Railo et al., 2008). For example, at 3.3°, a similar reduction of the perceived number of items in the subitizing range was found; however, only when the stimuli were not attended and perceptual demands were high (Railo et al., 2008). When the stimuli were attended and perceptual demands were low, accuracy in the subitizing range was close to 100% (Railo et al., 2008). Experiments investigating how viewing eccentricity affected enumeration performance found that accuracy in the subitizing range did not depend on eccentricity when the stimulus was scaled with eccentricity (Palomares et al., 2011; see also Parth & Rentschler, 1984). Critically, however, the stimuli were presented along a circular path at the same eccentricity (that is, in tangential arrangements), and the inter-target distance was sufficiently large to prevent crowding between neighboring items. In line with the results of the present study, these stimuli should not be subject to redundancy masking. Finally, a recent study investigating the effect of crowding on subitizing found that subitizing was impaired by crowding, and that increasing the inter-item spacing improved observer's performance (Chakravarthi & Herbert, 2019), in line with the results of our Experiment 1.

The "masking" of entire items was particularly evident when three lines were presented. As reporting two instead of the three presented lines corresponds to an omission of one-third of the stimulus, the observed deviation relative to the number of lines presented was maximal in this condition. Although the absolute number of lines lost due to redundancy masking tended to increase with the number of lines presented, the relative number decreased, showing that redundancy masking does not scale linearly with the number of items presented. We suggest that the difference between large and small numbers is due to different processes involved in the task. When small numbers were presented, observers subitized (or "saw") how many items were presented; however, they did so erroneously when redundancy masking occurred. When larger numbers were presented, estimation was necessary, possibly counteracting the strong relative loss by redundancy masking observed with smaller numbers.

In the experiments reported here, we found similarities and differences between crowding and redundancy masking. In redundancy masking, the reduction of the perceived number of items resembles a failure of detection. In contrast, detection is usually intact in crowding (Levi et al., 2002; Pelli et al., 2004). However, frequent omissions of elements reported for crowding do suggest that similar failures of detection can occur in typical crowding studies ("omission errors"; Coates et al., 2017; Coates et al., 2019; Sayim & Wagemans, 2017). These omission errors could well be due to the same underlying mechanisms as the effects reported here. Alternatively, they might not require the same regularity of patterns necessary for the occurrence of redundancy masking. In general, both omission errors and redundancy masking can be experimentally targeted and individually quantified, enabling the investigation of their relationship and contribution to the deterioration of performance in crowded identification. We suggest that redundancy masking does play a role in crowded identification when the presented stimuli contain highly regular, repeating patterns. Regarding the investigated variables in the present experiments, we found several parallels between crowding and redundancy masking. As noted above, redundancy masking was influenced by spacing, spatial arrangement, and regularity similar to crowding. We also found that redundancy masking was not affected (line length) or affected to some extent (line width) by target size, which partially resembles what is observed in crowding (Pelli et al., 2004; Tripathy & Cavanagh, 2002). However, whether the same mechanisms underlie crowding and redundancy masking, under what conditions the effects of redundancy masking are observed in standard crowding paradigms, and to what extent other visual phenomena such as masking and ensemble perception (see below) are related to redundancy masking is still unclear. Before a definite classification is possible, further characteristics of redundancy masking, and differences and similarities with the phenomena mentioned above have to be established.

Current accounts of crowding differ in regard to their ability to explain the effect of redundancy masking. In pooling models, the processing of crowded stimuli is modeled to occur in two stages: detection and integration (Chung et al., 2001; Greenwood, Bex, & Dakin, 2009; Levi et al., 2002; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli et al., 2004). At the detection stage individual features are preserved; but at the integration stage the positional information of those features is lost, thus causing crowding. Intact feature detection does not suggest a reduction of the perceived number of elements. However, the loss of positional information at the integration stage could potentially result in the erroneous extraction of the same positional code for two or more elements, or the averaging of positional codes for multiple elements, yielding redundancy masking. For example, the averaging of the positional codes of three lines could result in the merging of the central line with one of the two outer lines, resulting in the report of only two lines. In this framework, however, redundancy masking could just as well occur on the detection level without involvement of the integration stage. Importantly, redundancy masking also occurs for more complex items, such as letters, indicating that it either occurs at a stage after feature integration has taken place, or simultaneously for multiple elements that make up the lost target (Sayim & Taylor, 2019).

A related approach to explain crowding is based on statistical summary representations (Balas, Nakano, & Rosenholtz, 2009; Freeman & Simoncelli, 2011; Keshvari & Rosenholtz, 2016; see also Balas, 2016; Rosenholtz, Huang, Raj, Balas, & Ilie, 2012). According to these models, the visual system represents cluttered stimuli in the peripheral visual field with a substantial loss of information, using summary statistics. Originally applied in image processing to analyze and synthesize textures (Portilla & Simoncelli, 2000), statistical summary representations were successfully used in peripheral vision and crowding, capturing differences in discriminability between certain classes of stimuli (Balas et al., 2009). However, their efficacy has been shown to depend strongly on the task (Wallis, Bethge, & Wichmann, 2016) and the type of stimuli used (Wallis, Funke, Ecker, Gatys, Wichmann, & Bethge, 2019). Although it would be feasible that the information retained by statistical summary representations corresponded to what is maintained in redundancy masking, the effects of redundancy masking seem not to be replicated. For example, when applied to three identical letters "T", the loss of an entire letter was not captured by summary representations (Block, 2013), unlike the empirical observations (Sayim & Taylor 2019). This does not exclude that a different set of parameters might successfully replicate the loss of repeated items in redundancy masking.

The general role of spatial attention in crowding has been pointed out in many studies (He et al., 1996; He et al., 1997; Intriligator & Cavanagh, 2001; Scolari, Kohnen, Barton, & Awh, 2007; Strasburger, 2005; Strasburger et al., 1991; Strasburger & Malania, 2013; Yeshurun & Rashal, 2010). An attentional mechanism that could possibly underlie redundancy masking is (insufficient) attentional resolution (He et al., 1996; He et al., 1997; Intriligator & Cavanagh, 2001). Although the visual system would be able to visually resolve the presented items (with observers perceiving a set of separate lines), access to an individual item would be compromised. Such limits of attentional resolution were also proposed to underlie the effects of crowding on subitizing (Chakravarthi & Herbert, 2019). However, in contrast to what would be expected if redundancy masking was driven by attentional limits (He et al., 1996), we recently found that there was no asymmetry between the upper and lower visual field (Yildirim, Coates, & Sayim, 2019b). Rather, redundancy masking was stronger in the left and right visual field (on the horizontal meridian) compared with the upper and lower visual field (on the vertical meridian), which diverges from what is usually found in crowding (Fortenbaugh, Silver, & Robertson, 2015; Greenwood et al., 2017; He et al., 1996; Petrov & Meleshkevich, 2011b).

Another possibly related explanatory framework that could account for the present results is ensemble perception (Alvarez, 2011; Whitney, Haberman, & Sweeny, 2014; Whitney & Leib, 2018). In this framework, information about individual objects is lost when sets of objects are represented as an ensemble. For example, observers can accurately extract the mean size (Chong & Treisman, 2003), orientation (Ariely, 2001), and location (Alvarez & Oliva, 2008) of a number of objects without accurate representations of these features for each object. Redundancy masking could be due to such (imprecise) representations of ensembles of items. However, although ensemble representations may occur for as few as two objects, they are usually assumed to occur for larger numbers of objects (Whitney & Leib, 2018). Importantly, in ensemble perception features of objects, such as their size or orientation, not the *number* of objects is represented, and the clear and systematic underestimation of the number of lines (often by one-third when only two of three items are reported) is not easily accounted for by ensemble representations.

Besides crowding, the effect of redundancy masking also resembles standard masking (Breitmeyer & Öğmen, 2000; Breitmeyer & Öğmen, 2006; Enns & Di Lollo, 2000; for similarities of crowding and backward masking see Sayim, Manassi & Herzog, 2014). As in standard masking, the target signal is lost, and observers are unable to detect (one of) the target(s). However, several characteristics of redundancy masking suggest that standard masking and redundancy masking are distinct phenomena. Masking occurs when the mask overlaps with the target in space or time (Breitmeyer & Öğmen, 2006), but redundancy masking, like crowding, occurs with simultaneously presented elements without spatial overlap. Moreover, in masking, the critical spacing has been shown to scale with target size (Levi et al., 2002), whereas our results show that redundancy masking varies with size only to some extent. Importantly, unlike most masking studies, we used an enumeration task to examine redundancy masking because normal detection tasks in which participants report presence or absence of a target at a known location would not reveal redundancy masking. For example, using a subset of the stimuli of the present experiments, we asked observers to indicate whether the target was absent (two lines) or present (three lines), and found that performance was close to perfect (results not reported here). A similar task dependence was found in a recent study that showed strong redundancy masking when observers were asked to freely report and draw the entire stimulus (three letters “T”); however, when the observers identified the central of the three letters, performance was almost perfect (Sayim & Taylor, 2019). The resulting drawings of that study (as approximations of stimulus appearance), together with informal reports about the phenomenology of redundancy-masked stimuli, suggest some similarity to standard masking and a strong divergence from what is usually reported in crowding: as in masking, a target was lost, and neither the drawings, nor the informal subjective reports indicated that stimuli, which were subject to redundancy masking, were “jumbled” as they usually are in crowding. Rather, the identity of the items in these repeating patterns was remarkably clear.

Conclusion

We revealed several characteristics of redundancy masking: redundancy masking depended on the spacing between elements, it was strong with radially arranged lines and absent with tangentially arranged lines, it was influenced by target size to some extent, and it was strongly modulated by regularity. Redundancy masking shares features with other phenomena, such as crowding, masking, and ensemble perception. However, on a behavioral and a phenomenological level, redundancy masking diverges from each of these effects to some extent, and therefore cannot be classified with certainty to be based on the same underlying mechanisms.

Keywords: crowding, masking, diminishment, enumeration tasks, numerosity, ensemble perception, perceptual grouping, regularity

Acknowledgments

Parts of this work were presented at the European Conference on Visual Perception 2017 in Berlin, Germany. This work was supported by the Swiss National Science Foundation (PP00P1_163723 to Bilge Sayim). The data of this study are available in the BORIS (Bern Open Repository and Information System) repository, https://boris.unibe.ch/id/eprint/142941).

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