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Compression of visual information in redundancy masking follows grouping and segmentation

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ABSTRACT

In typical scenes, the available visual information exceeds the processing limits of the visual system. To reduce information, the visual system organizes visual input according to various principles. For example, in visual grouping local elements are grouped into larger wholes. Recently, it was shown how the visual system compresses redundant information by 'redundancy masking' which reduces the number of perceived items in repeating patterns. For example, when three identical items are presented in the periphery, observers often report perceiving only two items. In the current study, we examined the role of grouping and segmentation in redundancy masking. In particular, we asked whether visual grouping determines–and precedes—the units in which information is compressed in redundancy masking. Stimuli consisted of arrays of 3–5 vertical lines, briefly presented in the left or right visual field. We varied the contrast polarity of the lines to create the following patterns: uniform arrays, alternating arrays, and subgroups of identical lines with a different line at the stimulus edge. Observers reported the number of lines and then indicated the perceived feature values for each reported line. Our results revealed redundancy masking in all conditions. Importantly, redundancy masking always came after segmentation and grouping: lines were masked predominantly within segmented subgroups of identical lines. The reported patterns were highly systematic, even when redundancy masking occurred: The presence/absence of the two contrast polarities (Contrast), the stimulus edge (Edge) and their ordinal frequencies (Ratio) were largely accurately reported. Hence, important stimulus information remained largely intact.

We suggest that redundancy masking comes after grouping and segmentation, and that the visual system compresses redundant information in the visual periphery by reducing the number of perceived identical items while preserving key stimulus features.

1. Introduction

In most visual scenes, the amount of available information exceeds the human visual system's processing capacity. Several characteristics of the visual system help to cope with excessive information. For example, the visual system compresses redundant and nonessential information. In visual grouping, individual elements are combined into larger, cohesive wholes, and require less processing capacity than detailed representations of each individual element (Han & Humphreys, 2003; Kaiser, Stein, & Peelen, 2014; Kubovy & Van Den Berg, 2008; Wagemans et al., 2012; Wertheimer, 1922, 1923). A recently discovered phenomenon, 'redundancy masking' (RM), occurs when observers view repeating patterns: For example, when presented with three identical items in the visual periphery, observers often report seeing only two items (Sayim & Taylor, 2019; Taylor & Sayim, 2020; Yildirim, Coates, & Sayim, 2019, 2020, 2021; Yildirim & Sayim, 2022). Repetitive elements contain redundant information, which is compressed in redundancy masking to a smaller number of elements while maintaining the global gist of the stimulus.

Redundancy masking is distinct from visual crowding, although both involve interactions between nearby elements. Crowding refers to the interference of flanking elements with the identification or discrimination of a target (for reviews on crowding, see: Herzog, Sayim, Chicherov, & Manassi, 2015; Levi, 2008, 2011; Whitney & Levi, 2011)). In

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crowding, visual discrimination and identification are impaired by flanking elements, an effect particularly pronounced in the visual periphery (Bouma, 1970; He, Cavanagh, & Intriligator, 1996; Levi, 2008, 2011; Pelli, Palomares, & Majaj, 2004; Whitney & Levi, 2011). Crowding thus affects tasks that require fine discrimination, (Levi, Toet, Tripathy, & Kooi, 1994; Westheimer & Hauske, 1975), orientation discrimination (Andriessen & Bouma, 1976; Westheimer, Shimamura, & McKee, 1976), letter recognition (Bouma, 1970; Chung, Levi, & Legge, 2001; Chung & Mansfield, 2009; Flom, Weymouth, & Kahneman, 1963), and face and emotion perception (Farzin, Rivera, & Whitney, 2009; Kouider, Berthet, & Faivre, 2011; Louie, Bressler, & Whitney, 2007). Importantly, crowding does not reduce the detectability of the target: detection remains intact, while target identification is compromised (e.g., Pelli et al., 2004; Whitney & Levi, 2011). By contrast, redundancy masking refers to a reduction in the perceived numerosity or visibility of repeating, identical items. Instead of impaired identification, individual redundant elements (or subsets of elements) are perceptually inaccessible, yielding reports of fewer items than are physically present. This perceptual compression occurs even when the items are easily detectable in isolation and visual resolution is sufficient to resolve two neighboring items. Thus, whereas crowding is contextual interference that impairs discrimination, redundancy masking reduces the perceived number of items. The two phenomena therefore differ in the perceptual outcome: failures to identify a target vs. failures to detect all presented items.

Several other characteristics of redundancy masking show that it is distinct from crowding. For example, in contrast to crowding (and many other visual effects in peripheral vision; (see, e.g., Himmelberg, Winawer, & Carrasco, 2023), redundancy masking has atypical visual field asymmetries (Yildirim, Coates, & Sayim, 2022; Yildirim-Keles et al., 2024): Strongest redundancy masking occurs on the horizontal meridian and there is no upper-lower visual field asymmetry. Crowding effects are very weak or absent when the presented items (target and flankers) are identical (Sayim & Taylor, 2019) while redundancy masking is maximal with identical items and decreases with decreasing similarity (Sayim et al.). Other characteristics of redundancy masking include its dependence on regularity (with higher RM when items are arranged regularly) and size (thicker lines yield weaker redundancy masking) (Yildirim et al., 2020). Similar to crowding, redundancy masking depends on the spacing between items (weaker redundancy masking with larger spacings) and the arrangement relative to the fovea (stronger with radially compared to tangentially arranged items) (Yildirim et al., 2020).

In the current study, we examine whether redundancy masking occurs within or across perceptual units by investigating two key mechanisms of the visual system: grouping and segmentation. While grouping and segmentation have been shown to strongly influence crowding in the visual periphery (Herzog et al., 2015; Manassi, Sayim, & Herzog, 2012; Saarela, Sayim, Westheimer, & Herzog, 2009) their role in redundancy masking is largely unknown (but see Yildirim et al., 2020). Grouping and segmentation are fundamental principles of perceptual organization. Perceptual organization refers to the set of processes by which the visual system structures raw sensory input into coherent, meaningful percepts such as objects, surfaces and textures. Grouping is the process of perceptually linking elements that share common properties such as color, contrast, motion direction or spatial proximity. Segmentation is the complementary process of dividing the visual field into distinct regions based on differences in features, allowing individual elements to be distinguished from one another and from the background. For example, a red line among green lines stands out because of its color difference, which segments it from the surrounding elements. At the same time, the green lines, sharing the same color, are perceptually grouped and perceived as part of the same set or surface. Thus, segmentation isolates the red line as a distinct object, while grouping binds the green lines into a coherent unit. Functionally, segmentation enables the separation and identification of individual elements, whereas grouping promotes the integration of elements into larger perceptual units. Grouping and segmentation operate together: the visual system combines certain elements while separating them from other elements. Strong grouping within a region can simultaneously promote its segmentation from other regions, as grouped elements are often perceived as single units distinct from the background and from other objects. Conversely, clear segmentation boundaries can enhance grouping within those boundaries by reinforcing which elements belong to the same object or surface (Kimchi, Behrmann, & Olson, 2003; S. E. Palmer & Brooks, 2008; Wagemans, 2018; Wagemans et al., 2012). Grouping has previously been shown to be a key factor in determining interference among items in crowding (Manassi et al., 2012; Sayim, Westheimer, & Herzog, 2010): Interference is usually stronger when grouping among the target and the flankers is strong (Herzog et al., 2015; Manassi et al., 2012; Reuther, Chakravarthi, & Martinovic, 2022; Sayim, Westheimer, & Herzog, 2008; however, see Rummens & Sayim, 2021; Melnik et al., 2020; Melnik et al., 2018)). For example, when multiple identical flankers are perceptually grouped together and ungrouped from the target, the segmentation into target and surround (the flankers) improves target discrimination (Banks, Larson, & Prinzmetal, 1979; Banks & White, 1984; Herzog et al., 2015; Livne & Sagi, 2007; Malania, Herzog, & Westheimer, 2007; Sayim, Westheimer, & Herzog, 2011). Grouping and segmentation of targets and flankers are strongly affected by their similarity: A reduction of crowding strength has been observed when targets and flankers differed in color or contrast polarity (Chung et al., 2001; Hess, Dakin, & Kapoor, 2000; Levi et al., 1994; Manassi et al., 2012; Sayim et al., 2008), orientation (Levi, Hariharan, & Klein, 2002; Wilkinson, Wilson, & Ellemberg, 1997), spatial frequency (Levi et al., 2002; Wilkinson et al., 1997), shape (Kooi, Toet, Tripathy, & Levi, 1994; Nazir, 1992; Põder, 2006) differences in length (Malania et al., 2007; Saarela et al., 2009; Saarela, Westheimer, & Herzog, 2010). On all such instances, larger dissimilarity between target and flankers results in stronger ungrouping, hence, weaker crowding.

However, how grouping, and segmentation of items affect RM remains largely unexplored. Understanding how grouping and segmentation interact is important for characterizing redundancy masking. Although redundancy masking and visual crowding both involve interactions among nearby elements, they likely reflect different aspects of perceptual organization. In crowding, strong grouping between target and flankers can reduce segmentation and impair feature identification. In redundancy masking, by contrast, grouping among identical elements may lead to perceptual compression, with multiple items perceived as fewer than are physically present, while identification of the identical, repeating features across the presented items remains unimpaired. Examining how grouping and segmentation influence redundancy masking can therefore help clarify the perceptual mechanisms that give rise to this masking effect.

A central open question concerns the level of visual processing at which redundancy masking occurs. If RM arises before perceptual organization, it may reflect early sensory interactions or lateral inhibition among neighboring elements. If, however, RM depends on how elements are grouped and segmented, this would indicate that it emerges at a mid-level stage of visual processing, after the visual system has formed coherent perceptual units. Examining how grouping and segmentation influence redundancy masking therefore provides a way to clarify its locus within the visual hierarchy.

We investigated the role of grouping and segmentation in redundancy masking by manipulating the contrast polarity in arrays of radially arranged lines, presented in the visual periphery. Do perceptual grouping and segmentation within a line array affect the strength of redundancy masking? Does RM occur within, across or both within and across perceptual groups? We used an appearance-based approach (Coates, Wagemans, & Sayim, 2017; Sayim & Taylor, 2019; Sayim & Wagemans, 2017).

where observers are asked to reproduce (multiple features of) the entire stimulus, enabling a detailed comparison of differences between

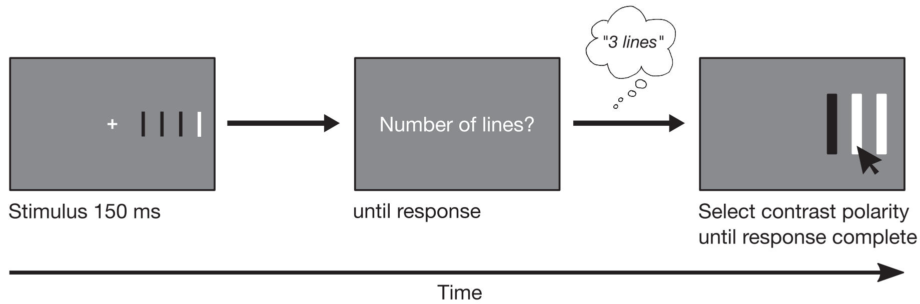

Fig. 1. Overview of the procedure of a single trial. After the presentation of the stimulus, observers were required to indicate how many lines they perceived. This number determined the number of lines that appeared for the second task. Using the computer mouse, they could click on the lines and switch their contrast polarity between black and white. (The example shows a four-line stimulus which was reported as three lines. Note, that sizes in the figure are rescaled for the readers' convenience).

the perceived and the presented stimulus. In the Supplementary material:, we provide Figures in which we replicated the experiment with isoluminant red and green lines.

2. Material and methods

2.1. Observers

20 observers (20–36 years old) participated in the experiment (A power analysis on effect sizes from a closely related redundancy masking experiment (R^2_reduced=0.12, R^2_full = 0.24), combined with the number of observations per experiment and an estimated ICC (interclass correlation) of 0.21, indicated that a minimum sample size of 12 participants was required). All observers were naïve to the purpose of the study and had normal or corrected-to-normal vision. All experiments were performed in accordance with the requirements of the local ethics committee at the University of Lille and the Declaration of Helsinki.

2.2. Task and procedure

Each trial began with a white fixation cross displayed in the center of the screen for 1 s. Afterwards the stimulus was presented for 150 ms to the left or right of fixation. Observers were asked to indicate the number of presented lines by pressing the corresponding number on the keyboard. After reporting the number, an array with the indicated number of lines appeared. For example, if an observer responded seeing three lines, three lines appeared. Observers could click on each line with the computer mouse to switch between white and black (Fig. 1). Observers were instructed to replicate the contrast polarities that they had perceived, creating “appearance matches” which we compared with the presented stimulus. They pressed the space bar when they were satisfied with their selection. Observers completed a total of 288 trials (2 blocks; see details below).

2.3. Apparatus

All stimuli were displayed on a 24-in. VPixx monitor. The resolution of the screen was set to 1920 × 1080 at 100 Hz. All stimuli were generated and displayed using Psychopy 2020.2.4 (Pierce, 2007) that ran on a Desktop PC. Observers viewed the screen from 57 cm supported by a chin and headrest in a dimly lit room.

2.4. Stimuli

Stimuli consisted of arrays of black and white lines that were 78′ in length and 4.9′ in width. The number of lines in each array ranged from 3 to 5 lines randomly selected at the beginning of each trial. The array was centered at 10° eccentricity either on the right or left of fixation. The inter-line spacing was the same between each two lines within a given array (lines were regularly spaced within the array), but inter-line spacing was varied across trials. In trials with three or four lines the following spacings were used: 48′, 81′ and 117′, and in trials with five lines: 48′, 69′ and 81′. These spacings were previously used to study redundancy masking and were all above the resolution limit to discern two neighboring lines (at least 95% correct responses for the smallest spacing at the largest eccentricity, Yildirim et al., 2020). We included different line spacings to prevent observers from using the overall stimulus size (total width) as a proxy for the number of lines in the stimulus. The pattern of contrast polarity of the lines within the arrays was chosen to create four different conditions: uniform (1), alternating (2), a difference in either the inner (3) or the outer (4) lines. Each condition was presented in two alternate versions, by reversing contrast polarity of the whole set (Fig. 2).

This resulted in a total of 144 trials (2 sides × 4 conditions × 3

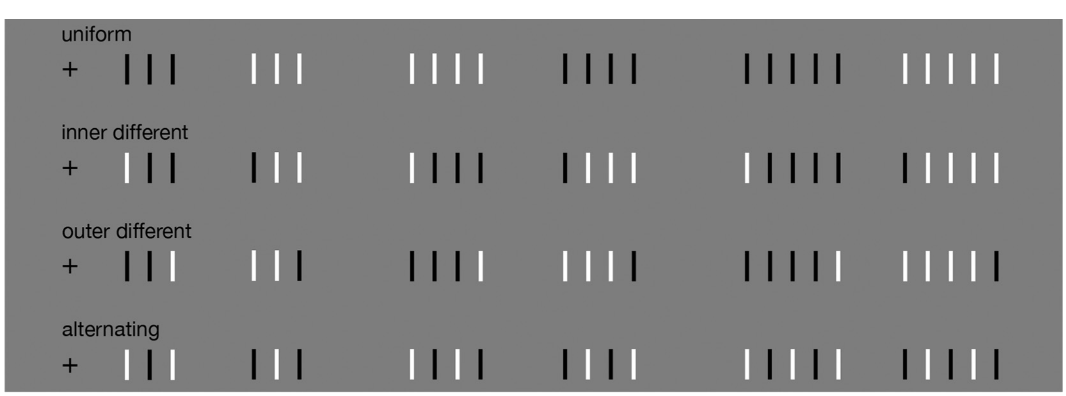

Fig. 2. Overview of the conditions for stimuli that are presented on the right side of fixation. Note that size and spacing is not to scale. The two columns for each line number refer to the two different contrast versions created for each stimulus.

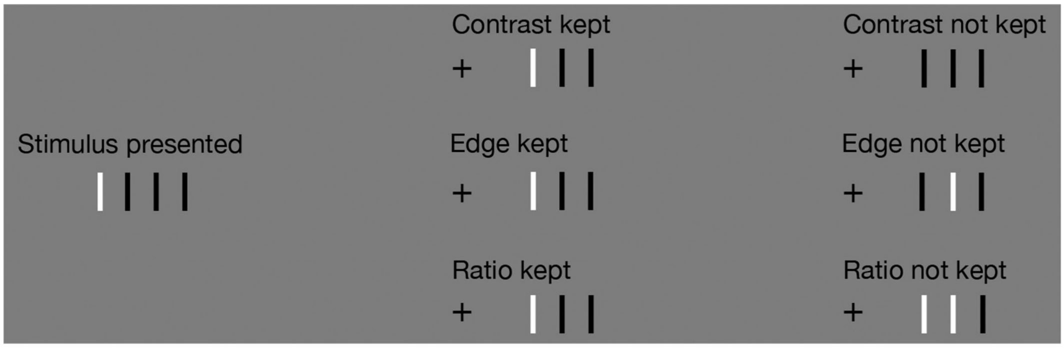

Fig. 3. Examples of appearance matches that match (central panel) or do not match (right panel) the global stimulus features Edge, Ratio, and Contrast. We examined three different global features: Stimulus Edge, Ratio and Contrast. Examples here are shown for a four-line stimulus in which the inner line was different. The same procedure was applied to all trials in which redundancy masking occurred.

number of lines (3–5) × 3 spacings × 2 contrast versions). These 144 combinations were repeated twice in two separate blocks resulting in 288 trials in total. The response lines were centered at 5° eccentricity either on the left or the right side of fixation. The presentation side on the screen was matched to the position of the presented stimulus and observers could freely move their eyes during the response phase. Individual response lines had a width of 0.75 degrees of visual angle and a length of 4 deg. VA. We chose a line width that participants could easily click on with the computer mouse.

2.5. Subjective ratings

To directly examine whether our different conditions elicit segmentation of the singleton line and grouping among the identically colored lines, we asked 10 new observers (6 females, age: 29.5) to rate how much the black and white lines appear as separate groups in the stimulus. Observers were presented with the same stimuli, at the same location in the periphery (except the uniform condition) and rated the strength of segmentation between the black and white lines on a scale with 0 corresponding to "completely separate groups" and 7 corresponding to "no separate groups at all" following a similar rating scale and procedure as the subjective ratings collected in Manassi et al. (2012).

2.6. Data analysis

Observer's performance was analyzed by calculating deviation scores as the number of lines presented subtracted from the number of lines perceived. Trials in which more lines were reported than presented had positive deviation scores; trials in which fewer lines were reported than presented had negative deviation scores; correct responses corresponded to deviation scores of 0.

Deviation scores and the number of different contrast polarity combinations selected by observers were analyzed by using linear mixed-effects models specifying observers as a random factor and the line number and contrast condition as fixed effects.

Analyses were performed with R (R Core Team, 2018), using the *lmer* function of the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015). For model selection, a null (intercept only), a reduced (line number), a full (line number and contrast condition as the fixed effects) and a full model with interactions were fitted and hierarchically compared. The random effect's structure contained random intercepts for each observer. The null, reduced, and full models were tested against each other applying a likelihood ratio test using $\chi 2$-statistics.

To obtain an initial overview of the most frequent appearance reports across our different stimuli, presentations of stimuli on the left side were mirrored onto the right side of fixation. For brevity, the two contrast versions for each condition are shown together, as both

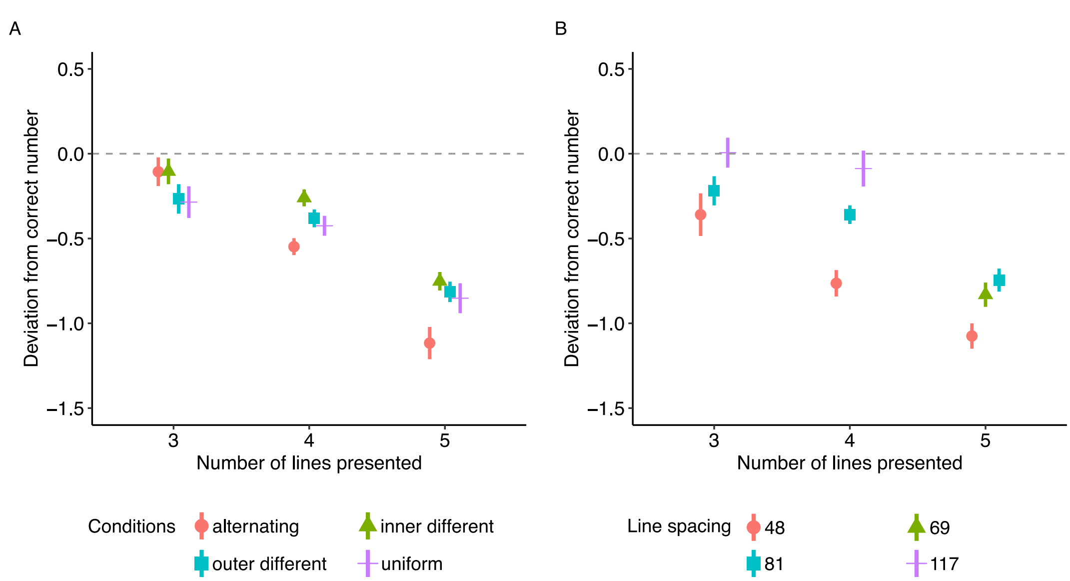

Fig. 4. Mean deviation scores as a function of the number of presented lines. (A) Deviation scores separated by condition and (B) deviation scores separated by line spacing. Error bars correspond to the 95% confidence interval (CI) adjusted for within-subject variability (Morey, 2008).

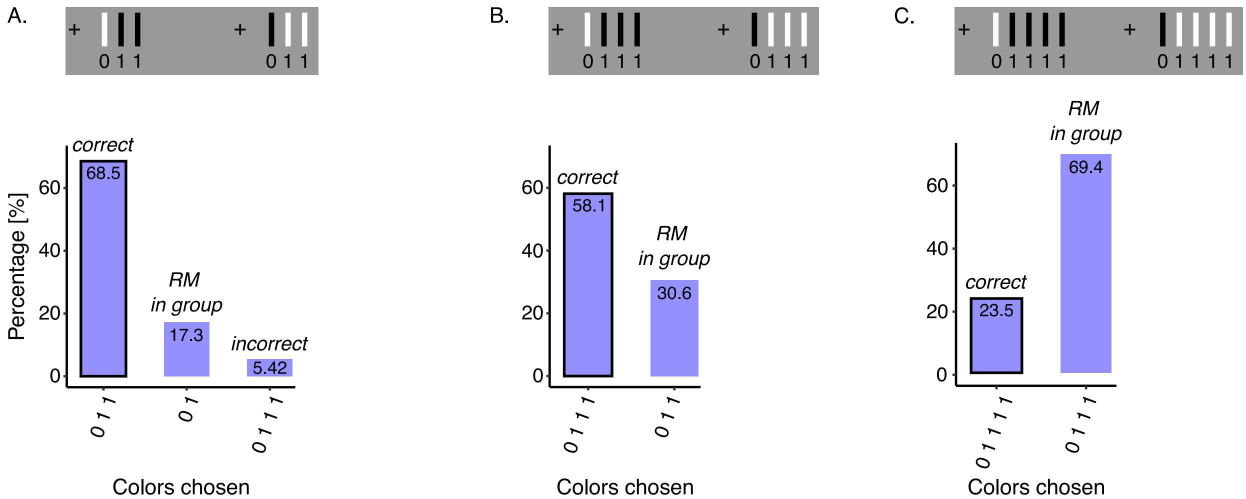

Fig. 5. Percentage of the different appearance matches created by observers when the line closest to fixation had the opposite contrast polarity of all other lines. The correct (presented) stimuli are shown on the top. Zeros and Ones represent the overall pattern of the stimuli, specifying which lines were identical (all 0 correspond to either black or white and all 1 s correspond to the other contrast polarity (white or black, respectively). The patterns are shown in their correct spatial arrangement relative to fixation. Each panel corresponds to a different line number: (A) three lines, (B) four lines, (C) five lines. Bars with a black outline correspond to the exact replications of the stimulus. Bars are grouped by the type of appearance. RM refers to redundancy masking and RM in group refers to redundancy masking occurring within the group of identical lines in the stimulus. Correct refers to a correct appearance match and incorrect refers to incorrect appearance matches. The numbers inside the bars correspond to the exact percentage.

manipulations yielded no systematic differences in deviation scores or in appearance matches. In the figures, contrasts are coded as 0 and 1 (e.g., the three-line stimuli black-white-white and white-black-black are both coded as 011). For each condition, we counted the number of distinct appearance matches to summarize how the stimuli were perceived by observers. These counts are displayed in simple bar plots to illustrate overall patterns. The plots are descriptive and serve only to provide a visual impression of the data; no statistical analyses are applied at this stage since only percentages are presented. The statistical analysis is conducted on the analysis of the global stimulus features.

In a second appearance analysis, we examined global stimulus features to determine which stimulus features are retained when redundancy masking occurs. We calculated the proportion of occurrences of the following relationships between the stimulus and the appearance match: (1) Contrast: proportion of the (in)correct reproductions of a stimulus as (non-)uniform (e.g., when black and white lines were presented, the contrast was correctly reported when the responses also contained black and white lines). (2) Edges: proportion of the (in)correct reproductions of the two outermost lines of a target array (e.g., when the leftmost line was white and the rightmost line black, edges were correctly reported when the leftmost line was white and the rightmost line black as well), (3) Ratio: proportion of the (in)correct reproductions of the majority/minority of line polarities (e.g., when the stimulus contained more black than white bars, the Ratio was correctly reported when the response also contained more black than white bars). Fig. 3 shows examples of different appearance matches in which those global stimulus features were maintained or violated.

3. Results

3.1. Redundancy masking

Overall, deviation scores were mostly negative, revealing frequent occurrences of redundancy masking across all conditions (Fig. 4). Observers often perceived fewer lines than presented. The likelihood ratio test showed that the full model was better than the reduced model ($\chi2(3) = 42.99$, $p < .001$) and the full model with the interaction was better than the full model without the interaction ($\chi2(6) = 53.39$, $p < .001$). Hence the full model with interaction was selected. Both, line number and contrast condition influenced deviation scores. Our data also revealed an interaction between line number and contrast condition. The interaction is particularly visible for the alternating contrast polarity condition, where redundancy masking was much stronger for four and five lines compared to three lines and compared to the other contrast conditions.

Taken together, there was strong redundancy masking, and its strength depended not just on the number of lines in the stimulus but also the different conditions (combinations of lines). Observers reported fewer lines than the number of lines each stimulus was made of.

Recent studies showed that the strength of redundancy masking depends on the spacing of the lines in the stimulus. Small spacings up to 81 arcmin showed reliable redundancy masking, while for larger spacings (151′ to 186′) redundancy masking was reduced or even fully absent. We, therefore, presented observers with spacings smaller than 117′. Fig. 4B shows the deviation scores as a function of line number and line spacing. When the inter-line spacing was small (48′–81′), the average deviation scores were clearly below zero, while for the largest spacing (117′) deviation scores were around zero. A likelihood test showed that the full model was better than the reduced model ($\chi2(1) = 115.11$, $p < .001$) and the full model with the interaction was better than the full model without the interaction ($\chi2(1) = 15.69$, $p = .0013$). Hence the full model with the interaction was selected showing the effect of line number and line spacing on redundancy masking.

3.2. Appearance matches of the different stimuli: The role of grouping and segmentation

Besides reporting the number of perceived lines, observers were asked to replicate the contrast polarity of the individual lines they perceived. This allowed us to precisely study how a redundancy masked stimulus appeared to observers. To avoid analyzing random mistakes of observers, only appearance matches that occurred in more than 5% of all trials were selected for further analysis.

As shown in previous experiments, redundancy masking occurs frequently in uniform stimuli. We replicated these previous results in the uniform condition: In 33.8% of trials containing three lines, observers reported perceiving two lines; in 45.0% of trials with four lines, three lines were perceived; and in 70.4% of trials with five lines, four lines

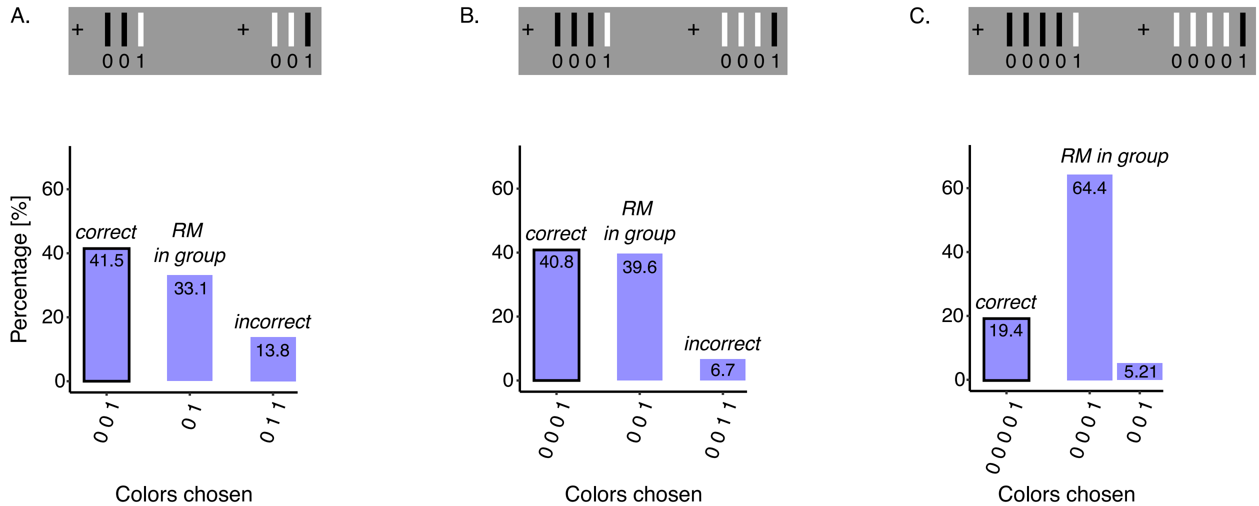

Fig. 6. Percentage of the different appearance matches created by observers following the presentation of a stimulus where the line furthest away from fixation differed. The correct (presented) stimuli are shown on the top. Zeros and Ones represent the overall pattern of the stimuli, specifying which lines were identical (all 0 correspond to either black or white and all 1 s correspond to the other contrast polarity (white or black, respectively). The patterns are shown in their correct spatial arrangement relative to fixation. Each panel corresponds to a different line number. Bars with a black outline correspond to the exact replication of the stimulus. Bars are grouped by the type of appearance. RM refers to redundancy masking and RM in group refers to redundancy masking occurring within the group of identical lines in the stimulus. The numbers inside the bars correspond to the exact percentage. Correct refers to a correct appearance match and incorrect refers to incorrect appearance matches.

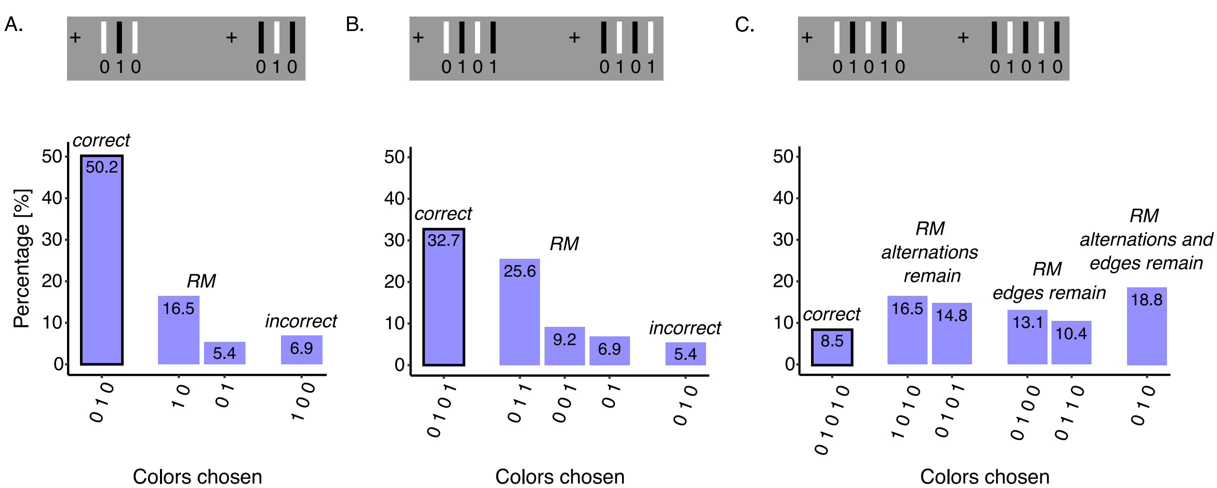

Fig. 7. Percentage of the different appearance matches created by observers following the presentation of a stimulus with alternating black and white lines. The correct (presented) stimuli are shown on the top. Zeros and Ones represent the overall pattern of the stimuli, specifying which lines were identical (all 0 correspond to either black or white and all 1 s correspond to the other contrast polarity (white or black, respectively). The patterns are shown in their correct spatial arrangement relative to fixation. Each panel corresponds to a different line number (3–5 lines). Bar containing a black outline correspond to the correct appearance capture. Bars are grouped by the type of appearance. The numbers inside the bars correspond to the exact percentage. RM refers to redundancy masking with the additional information whether the edges or the alternating lines remained in the redundancy masked stimulus. Correct refers to a correct appearance match and incorrect refers to incorrect appearance matches.

were perceived (in 7.5% of these trials, three lines were perceived).

The main goal of our experiment was to determine whether redundancy masking also occurs when lines have different contrast polarities. For non-uniform patterns, the appearance-based analysis allowed us to identify in which (parts of the) stimuli redundancy masking occurred, and how it related to visual grouping mechanisms. To obtain an overview of how the different stimuli appeared to observers and to quantify which appearances were the most frequent, we first counted the different appearance matches for each stimulus presented in the experiment. Fig. 5–7 summarize the proportion of appearance matches across all stimuli, providing a descriptive overview. Since these represent raw proportions, no further statistical analysis was performed. Each stimulus was presented in two contrast polarities, which were collapsed and coded as 0 and 1 (see Data analysis for details). Each Figure panel shows the correct responses on the top. Bars are labelled to indicate whether the appearance match was correct (leftmost column) or incorrect, and whether redundancy masking occurred (i.e., omission of lines). Fig. 5 shows all responses for stimuli in which the line closest to fixation was different ("inner different" condition, see also Fig. 2). All other lines in these stimuli had the same contrast polarity. In appearance matches that showed redundancy masking, predominantly a line from the group of lines with identical contrast polarity was not reported ('RM in group'). For example, a BWWW stimulus was reported as BWW, a BWWWW stimulus was reported as BWWW and rarely, a BWW stimulus was reduced to BW. Observers correctly identified the stimulus as containing two contrast polarities and always indicated the correct position of the

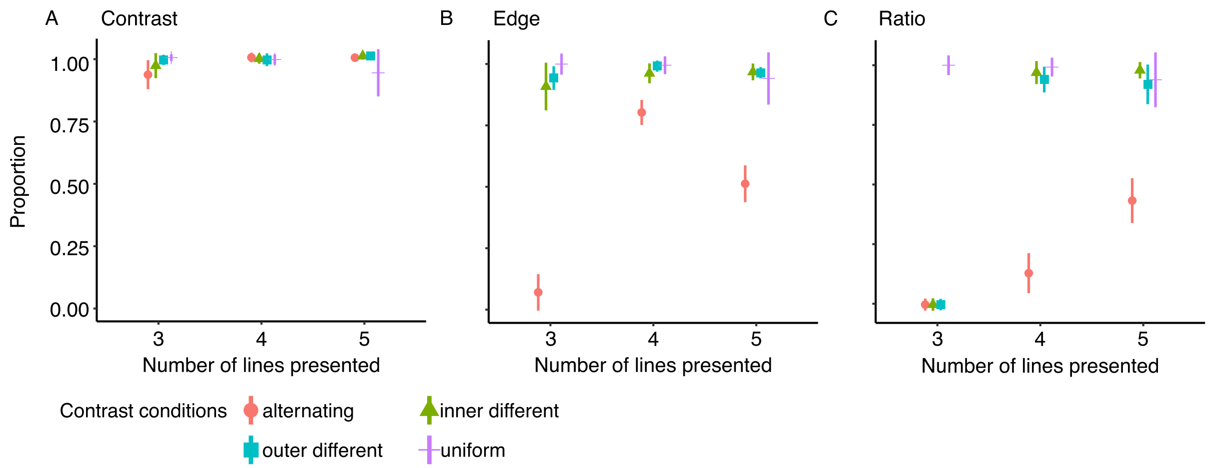

Fig. 8. Global stimulus appearance analysis. Each panel plots the proportion of trials in which one of the global stimulus features was kept within the appearance match that followed a trial in which redundancy masking occurred. A) Proportion of trials in which the Contrast was retained in the appearance match. B) Proportion of trials in which the Edge was retained in the appearance match. C) Proportion of trials in which the Ratio was retained in the appearance match. Error bars correspond to the 95% CI adjusted for within-subject variability (Morey, 2008).

singleton line (inner side of the stimulus, labelled as 0 in the Figure).

Fig. 6 shows all appearance matches for stimuli in which the line furthest from fixation was different ("outer different" condition). Similar to the results from the "inner different" condition, appearance matches in trials with redundancy masking showed that predominantly a line from the group of identical contrast polarity was omitted. For example, a WWWB stimulus was reported as WWB, a WWWWB stimulus as WWWB and a WWB stimulus as WB. Observers correctly identified the stimulus as having a singleton line on the outer side of the stimulus (away from fixation). Redundancy masking mainly occurred within the group of identical lines.

Appearance matches in the alternating conditions are shown in Fig. 7. Redundancy masking occurred less frequently for stimuli consisting of three lines, the number of missed lines increased for 4, but especially for 5 alternating line arrays. Alternating stimuli consisting of four lines were sometimes reported as containing only three lines (Fig. 7 middle panel, bars labelled RM).

The highest frequency of redundancy masking (missing entire lines in the stimulus) was observed with five alternating lines. On only 8.5% of the trials, observers reported the stimulus correctly. On most trials observers perceived either four or three lines. A reduction to three lines resulted in a symmetrical appearance match (Fig. 7C, bars in last group), that contained the same outer lines and the contrast polarity of the center as in the stimulus presented to the observer. On trials in which the stimulus was perceived as a four-line stimulus, observers either correctly report the alternating lines, which resulted in an incorrect report of the outer lines (Fig. 7C, right panel, bars labelled RM alternations remain), or incorrectly reported the alternations but reported the outer lines correctly (Fig. 7C, right panel, bars labelled RM edges remain).

Overall, these observations showed that redundancy masking occurred in alternating line arrays as well. Moreover, the frequency of different appearance matches showed very systematic appearances. Lines were mainly not reported when they were in the group of identical lines. In the alternating conditions, redundancy masking occurred as well and resulted either in stimuli in which the alternating pattern was kept, or the edges of the stimuli (innermost and outermost lines) were kept, and lines were dropped from the center of the stimulus. A global feature analysis including a statistical analysis was conducted to formalize these observations (see below).

3.3. Global stimulus feature analysis

Our results show that the strength of redundancy masking differed between the line conditions. To quantify which global features of the presented stimulus were maintained, we analyzed different global stimulus features and whether they remained present in the appearance match (for all trials in which redundancy masking occurred).

Fig. 3 in the Method section shows examples of different appearance matches in which those global stimulus features were maintained or violated. For all trials in which observers perceived fewer lines than in the presented stimulus, we analyzed whether these global features (Contrast, Edges and Ratio) were correctly or incorrectly reported.

Fig. 8 shows the proportion of trials for which these global features were maintained for all trials where redundancy masking occurred. Each panel corresponds to one of the three different global features tested. Generally, the Contrast (presence of black and white lines), the stimulus edges, and the Ratio of the lines were correctly identified. Fig. 8A shows the proportion of trials in which observers correctly identified the Contrast of the stimulus. In more than 96% of all trials, contrast polarity was correctly identified. Fig. 8B shows the proportion of trials in which the Edges of the stimulus was retained. In such cases the correct contrast polarity of the outer lines is maintained. For the uniform stimuli as well as stimuli where only one line differed, the edge and hence the two outer lines were correctly replicated in more than 95% of trials.

The edges were less often correctly reported in the alternating conditions. Here, the edges were only correctly reported in 55% of the trials. The reduction by one line - changes the stimulus from an even to an odd number of lines or vice versa. Maintaining the alternating pattern in redundancy-masked trials forces the omission of one line at the edge. For example, a WBWBW stimulus is reduced to WBWB or BWBW. Here, one of the lines at the edge drops. A four-line stimulus where the contrast polarity of the lines is inherently asymmetrical was often perceived as a three-line stimulus. Observers tended to retain the asymmetry and hence, the stimulus edge by missing one of the two central lines: A WBWB-stimulus is reduced to a WBB stimulus, and a BWBW-stimulus is reduced to BWW.

Likelihood ratio tests confirmed these observations. The full model with the interactions provided the best fit (this model was better than a model without the interaction or a reduced model). This interaction was mainly driven by the alternating condition that differed from the other conditions (full model with interaction vs. full model without interaction: $\chi2(6) = 153.15$, $p < .001$.

Fig. 8C shows the proportion of trials in which observers kept the same Ratio between the response and the stimulus. Any three-line stimulus that is reported as two lines cannot maintain this Ratio. In the four- and five-line condition the ratio was kept on the majority of

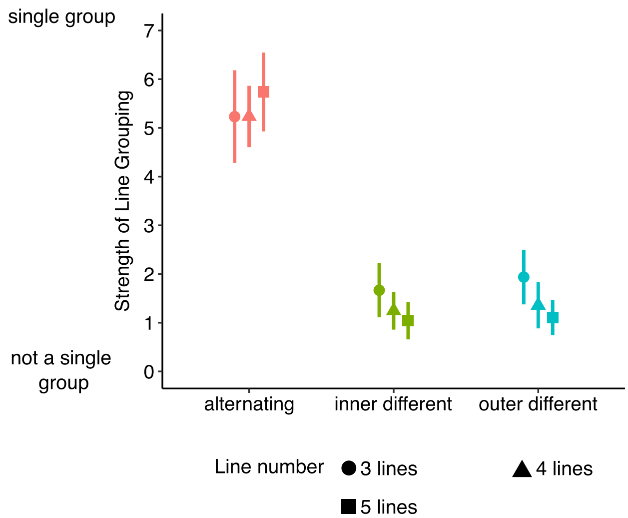

Fig. 9. Subjective ratings of perceptual grouping between black and white lines. The y-axis represents perceived grouping strength, ranging from **0** (black and white lines perceived as completely separate groups; strong segmentation) to **7** (no perceived separation; black and white lines perceived as a single integrated stimulus). The x-axis corresponds to the three different conditions used in the rating experiment and each dot corresponds to a specific line number between three and five. Error bars correspond to the 95% CI adjusted for within-subject variability (Morey, 2008).

trials (93% of all trials). For the alternating stimulus, this proportion was much lower. Any line reduction alters the original and the perceived stimulus from an odd to an even number of lines (or vice versa). This often affects the Ratio as well. An alternating four-line stimulus has an equal ratio of black and white lines. Perceiving such a stimulus as having only three lines automatically results in a violation of the original equal ratio. The number of trials in which the ratio is maintained is hence reduced in the alternating condition in both experiments. The full model with the interactions provided the best fit (this model was better than a model without the interaction or a reduced model). This interaction was mainly driven by the alternating condition that differed from the other conditions (full model with interaction vs. full model without interaction: $\chi 2(6) = 294.16$, $p < .001$ and $\chi 2(6) = 193.7$, $p < .001$.

Taken together, redundancy masking frequently occurred but showed highly systematic patterns: The missing line within the stimuli was predominantly from the group of identical lines. Even on trials in which less lines were reported, crucial global stimulus features such as the Edges, the Ratio and the Contrast in the stimulus were perceived and replicated correctly.

3.4. *Strength of segmentation*

Our results clearly showed that redundancy masking occurred within the group of lines with identical contrast polarity in the "inner different" and "outer different" condition and within regular alternating pattern while the singleton line was never masked. In a subjective rating experiment, we asked 10 new observers to rate how much the black and white lines appear as separate groups on a scale with 0 corresponding to "completely separate groups" and 7 corresponding to "no separate groups at all". Fig. 9 shows an effect of segmentation between the lines in the inner and outer different condition compared to the alternating condition. The difference between the singleton line and the group of lines with identical contrast polarity provided a cue for segmentation, while the alternating black and white lines were most often perceived as a single unit without any strong grouping into subgroups. The overall number of lines in the stimulus did not contribute to the strength of grouping or segmentation. A reduced model with only the conditions as a factor provided the best fit to the data with no further contribution induced by the number of lines $\chi 2(2) = 150.19$, $p < .001$.

4. Discussion

Redundancy masking is the reduction of the number of perceived items in repeating patterns. For example, when three radially arranged lines are presented in the visual periphery, observers often report perceiving only two lines. In redundancy masking, redundant information is compressed by the visual system: The global characteristics of a stimulus, such as its regularity and that it is a set of identical items, are maintained, but (subsets of) individual items are not represented and cannot be reported.

Here, we examined the role of grouping and segmentation in redundancy masking. Observers reported the number of perceived lines and reported the contrast polarity of each line. Overall, redundancy masking occurred on 49.7% of trials. To investigate whether and to what extent grouping and segmentation of the arrays of lines impacted the strength of redundancy masking, we used symmetric and asymmetric patterns of lines. We found redundancy masking in most of the conditions. Importantly, lines were predominantly masked from the group of lines that had identical contrast polarity.

In the "inner different" and "outer different" condition, a subgroup of lines within the line array was likely to be grouped by sharing the identical contrast polarity and segmented from the single dissimilar line. For example, an array consisting of three black lines and a white line at one of the edges (black-black-black-white) was expected to be perceptually segmented at the contrast polarity border into an array of three uniform (black) lines and a single (white) line. Color and contrast can act as a strong segmentation cue and help separate objects from their surroundings, while uniform color or contrast regions allow for grouping elements as belonging to the same object (Frome, Buck, & Boynton, 1981; McIlhagga, Hine, Cole, & Snyder, 1990; Mély, Kim, McGill, Guo, & Serre, 2016; Rivest & Cabanagh, 1996). Furthermore, visual crowding experiments investigating the role of grouping and segmentation on target perception showed that strong target-flanker grouping resulted in strong crowding, and weak target-flanker grouping, with the target segmented from the flankers, in weak crowding (e.g., Manassi et al., 2012; Saarela et al., 2009; Sayim et al., 2008, 2010, 2011). As it has been

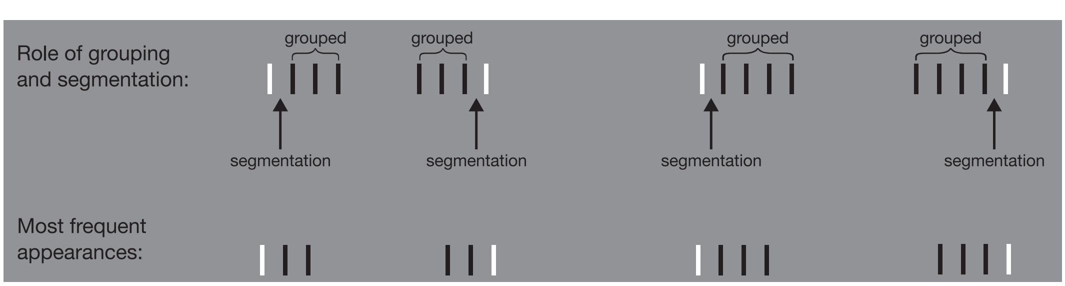

Fig. 10. Overview of the most frequent appearance matches for stimuli that contained segmented subgroups. Redundancy masking occurred within the subgroup of identical lines.

previously reported, redundancy masking frequently occurs with three or more lines (Sayim & Taylor, 2019; Taylor & Sayim, 2020; Yildirim et al., 2019, 2020, 2021, 2022; Yildirim & Sayim, 2022). Our results are in line with these findings: redundancy masking occurred predominantly within the segmented subgroup, and when the segmented subgroup consisted of a minimum of three lines. In the three-line condition, segmentation of the stimulus with two identical neighboring lines and one different line at one of the edges likely yielded a subgroup consisting of only two lines. On such trials, redundancy masking occurred on average in only 13.8% of trials. In all these trials, one of the two identical lines was masked. When three or more identical lines were placed next to each other, redundancy masking occurred within the segmented subgroup (Fig. 10). Redundancy masking thus followed the grouping and segmentation mechanisms: Identical lines in the stimulus were grouped before redundancy masking occurred.

Interestingly, on all trials in which lines from the subgroup were masked, the remaining line array was perceived highly systematically: Global stimulus features, including the Edges outermost lines), the Contrast (reproduction of a uniform or nonuniform stimulus), and the Ratio (reproduction of the majority/minority of line polarities) were mostly correctly reported. Hence, crucial information about the line arrays was preserved, while lines from neighboring, identical subgroups of lines were masked. Redundancy masking seems to occur predominantly in repeating patterns with a minimum of three repetitions, while non-repeating, unique features are maintained.

Previous work examined which of the lines within uniform line arrays was masked (Sayim, Oztas, L-Miao, & Alp, 2024; Yildirim et al., 2019). For example, observers were asked to report the spacing between the outermost lines, the spacing between neighboring lines and the location of a probe relative to the edges and the centroids of the stimulus arrays. The results revealed that the middle of three lines was masked from the array, and the two outermost lines were reported. In the present study, stimuli with three neighboring identical lines and a single different line were often reported as line triplets consisting of two identical and a single different line. While it is not possible with the current paradigm to determine which from the three identical lines was masked, the results of previous experiments with uniform line arrays suggest that the central line of the subgroup of three identical lines was masked (and one or two of the central lines when more than three neighboring identical lines were presented). Redundancy masking between items with different features seems to be weaker compared to identical items, hence, it is less likely that the line of the triplet of identical lines directly neighboring the different line was masked.

The present findings indicate that grouping and segmentation precede redundancy masking, suggesting that redundancy masking operates on organized perceptual units rather than directly on raw visual input. The subjective ratings align with this interpretation: In both the “inner different” and “outer different” conditions, black and white lines were perceived as strongly segmented into separate groups, consistent with grouping by contrast polarity while the alternating black and white lines did not result in strong grouping by contrast polarity. Observers were more likely to perceive the regular alternating pattern as a single unit. This has important theoretical implications: it implies that redundancy masking is not merely a low-level sensory phenomenon (e.g., due to early-stage lateral inhibition or normalization) but rather reflects a higher-level process that acts after perceptual organization has established groups and segmented object boundaries. Once elements are grouped into coherent units, redundant (or identical) elements within these units were frequently masked or integrated with neighboring elements, reflecting perceptual compression. Here, masking refers to a reduced perceptual availability of individual elements in our stimuli, such that they are no longer distinctly represented but are potentially integrated with surrounding elements. This interpretation aligns with the view that the visual system prioritizes efficiency by eliminating redundancy within perceptual groups, maintaining primarily information necessary for identifying and localizing objects (Beck, 1983; Kon & Francis, 2023; Lee & Yuille, 2006; S. Palmer & Rock, 1994). In this sense, redundancy masking might be viewed as a manifestation of the visual system's tendency toward efficient coding, reflected in the reduced representational load associated with repetitive information (Attneave, 1954; Simoncelli & Olshausen, 2001). At the same time, our results show that segmentation preserves key stimulus features, indicating that compression operates selectively within grouped regions rather than at random locations in the stimulus.

Surprisingly, redundancy masking also occurred in the alternating conditions. It was particularly strong with five lines, intermediate with four lines, and much weaker with three lines. In arrays with larger numbers of lines, all lines might have been grouped into an alternating pattern without any of the lines standing out from the array. Here, lines are not grouped by their contrast polarity but grouped due their global regularity and their regular alternations, forming potentially a texture-like group. When three alternating lines were presented, however, the central line was flanked by two lines of a different contrast polarity which ungroups the central line from the flanking lines. Such ungrouping between the three lines is expected to yield no redundancy masking, and our results indeed showed that three alternating lines were less likely to be reported as two lines (75.42%). Similar effects of grouping into alternating patterns, and ungrouping when only very few items (often one target and two flankers) are presented, have been reported in visual crowding. In particular, opposite contrast polarity of a target and the flankers results in uncrowding and improved discrimination performance of the central target compared to identical contrast polarity of the target and the flankers (e.g., Chakravarthi & Cavanagh, 2007; Chung & Mansfield, 2009; Kooi et al., 1994; Manassi et al., 2012; Nazir, 1992; Sayim et al., 2008). However, when adding more flankers of alternating contrast polarity, performance strongly deteriorates as the central target does not stand out from the flankers but groups with the flankers into an alternating pattern (Manassi et al., 2012; Sayim et al., 2008). Similar grouping mechanisms may underlie the present findings with larger numbers of lines (in particular five lines): The alternating lines were grouped and –in contrast to the three-line condition— none of the lines stood out from the pattern. Interestingly, when not only the central items but all three items of a triplet had to be reported in a crowding paradigm, instead of the typical advantage of opposite contrast polarity, better performance was observed for letter triplets with the same contrast polarity (similar to our Uniform condition): Uniformity improved discrimination performance when all three letters had to be reported (Rummens & Sayim, 2021; see also (Rummens & Sayim, 2019; Rummens & Sayim, 2022)). This uniformity advantage appears to occur in experiments that require the identification of all (three) items, possibly because of a cost due to compulsory segmentation of the stimulus (Rummens & Sayim, 2021). In the present study, observers were not required to identify the targets but only had to detect them (number task) and report their contrast polarity. If the two outer lines ungroup from the central line, detection performance of all lines is expected to be high. This is what we found here: For alternating line triplets with three lines, no redundancy masking occurred.

The response to alternating line patterns retained the global features differently compared to the other conditions. Alternating lines had symmetrical contrast polarity arrangements when the line number was odd and asymmetrical contrast polarity arrangements when the line number was even. Hence, the line arrays started and ended with either the same or with different lines. When observers reported one line less than was presented, it resulted in a change of the (a)symmetry in the stimulus, also affecting the reported Edges and Ratio. When a five-line stimulus was reported as four lines, the original organization of the array could not be maintained, leading to two different outcomes: the global alternating pattern was preserved, with (1) maintaining the regularity but inaccurately reporting the edges of the stimulus, or (2) preserving the outer lines (edges) but losing the global, alternating pattern. The alternating four-line arrays showed similar patterns when redundancy masking occurred: Either the edges or outer lines were

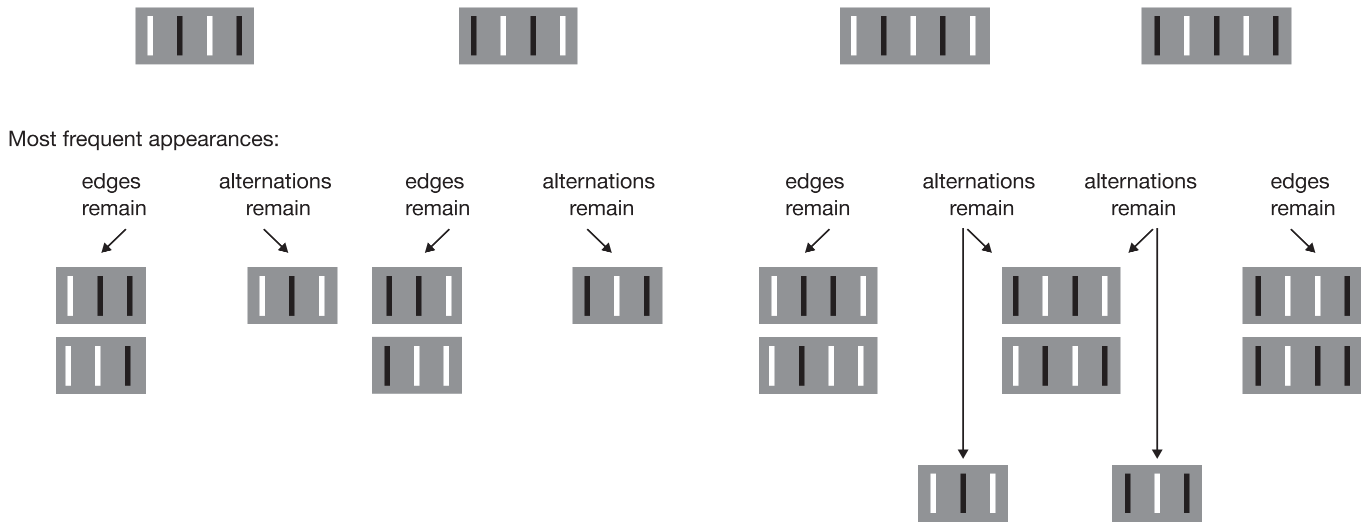

Fig. 11. Overview of the most common reported appearances of the alternating four- and five-line stimuli. The top panel shows the presented stimuli, and the lower panel shows an overview of the two typical appearance matches: Maintaining the edges of the stimuli or maintaining the alternating pattern. 5 lines were sometimes reported as three lines (shown in the lower right corner).

perceived and replicated correctly, or the alternating pattern was maintained, which resulted in incorrect replications of the edges of the stimuli. Fig. 11 visualizes these two different outcomes for the alternating five- and four-line stimuli.

One additional response type we observed in the alternating five-line condition was that observers occasionally reported only three lines with the alternating line pattern intact (18.75%). This results in the same symmetrical pattern as in an array with five lines. As a result, the deviation scores for the alternating five-line condition were much higher than for all other conditions.

Overall, our results showed that redundancy masking persisted even when the contrast polarity of the lines was not identical or regular but varied within the stimulus. Redundancy masking was weakened in the three-line condition when line contrast differed, but frequently occurred for stimuli with four or more lines, even when lines did not have identical contrast polarity. Grouping and segmentation precede redundancy masking, which operates on organized percepts. Hence, the compression of information in redundancy masking occurs within regular patterns or groups when grouping has been established. While redundant information was regularly masked, the contrast polarity of the stimulus and the ratio between the black and white lines were mostly correctly reported, as were the stimulus edges. Identifying the outer edges of any object in the visual field allows for object or texture segmentation from the background (Beck, 1994; (Beck et al., 1987), Grossberg, 1997; Grossberg & Pessoa, 1998), while surface or object interiors are more susceptible to redundancy masking. Edges give information about the location and size of the stimulus, which is crucial information for grasping or interacting with objects, while information from the center of the stimulus and subgroups of identical lines –where lines were predominantly masked in our experiment—is less important.

Taken together, our findings suggest that redundancy masking arises at a mid-level stage of visual processing, after basic feature detection and the initial grouping and segmentation of visual information. At this stage, elements have already been perceptually organized according to perceptual grouping principles, and the visual system selectively reduces redundant information within these groups. This suggests that redundancy masking reflects a process of perceptual compression or efficient coding acting on structured representations, rather than a limitation of early sensory encoding. In this view, redundancy masking serves to simplify visual input by downweighing repetitive information while preserving essential structural features such as edges, salient patterns, and distinctive features.

CRediT authorship contribution statement

Sabrina Hansmann-Roth: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wolf M. Harmening:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Bilge Sayim:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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All raw data can be found here: https://osf.io/29enc/

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2026.106507.

Data availability

All raw data is shared on OSF and found under the following link: https://osf.io/29enc/

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