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Detection vs. grouping thresholds for elements differing in spacing, size and luminance. An alternative approach towards the psychophysics of Gestalten

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ABSTRACT

Three experiments were performed to compare thresholds for the detection of non-uniformity in spacing, size and luminance with thresholds for grouping. In the first experiment a row of 12 black equi-spaced dots was used and the spacing after the 3rd, 6th, and 9th dot increased in random steps to determine the threshold at which the observer detected an irregularity in the size of the gaps. Thereafter, spacing in the same locations was increased further to find the threshold at which the observer perceived four groups of three dots each (triplets). In the second experiment, empty circles were used instead of dots and the diameter of the circles in the first and second triplet increased until the difference in size gave rise either to a detection or grouping response. In the third experiment, the dots in the second and fourth triplet were increased in luminance. The aim again was to compare the difference in brightness required for detection or grouping, respectively. Results demonstrate that the threshold for perceiving stimuli as irregularly spaced or dissimilar in size or brightness is much smaller than the threshold for grouping. In order to perceive stimuli as grouped, stimulus differences had to be 5.2 times (for dot spacing), 7.4 times (for size) and 6.6 times (for luminance) larger than for detection. Two control experiments demonstrated that the difference between the two kinds of thresholds persisted even when only two gaps were used instead of three and when gap position was randomized.

1. Introduction

Ever since Wertheimer's (1923) pioneering article on figure-ground organization, the Gestalt grouping laws proposed by him have been the subject of attention in perception research. Numerous papers have been written on the subject (recent examples are Pelli et al., 2009; Pinna & Reeves, 2006), however, only a few have aimed at quantifying the Gestalt laws (see Sarris, 1987). Among those, the Gestalt factors of proximity and similarity have been studied more than others (Claessens & Wagemans, 2005, 2008; Hochberg & Silverstein, 1956; Kubovy, Holcombe, & Wagemans, 1998; Kubovy & van der Berg, 2008; Kubovy & Wagemans, 1995; Oyama, 1961; Oyama & Miyano, 2008). None of these studies deals directly with perceptual grouping vis-à-vis the detection of non-uniformity.

There is little information in the literature about the relationship between detection thresholds and grouping thresholds, and one may therefore argue that to obtain a percept of grouping, a small difference in an otherwise uniform arrangement of elements would be sufficient. For example, grouping due to proximity might occur, because some elements are closer towards each other than others; analogously, grouping due to similarity might occur because some elements are equal, while others are not. However, the size of the difference required for detecting a non-uniformity among elements as opposed to seeing them as grouped has not been specified.

Wertheimer (1923) came close to this task by demonstrating that a matrix of dots could be perceptually grouped either in vertical or horizontal columns, depending on the spacing between dots (his Figs. 2e and f, p. 306). Yet, he mentions no measurements of detection vs. grouping thresholds. On the other hand, Wolfe (1992), in an experiment on pop-out in texture segmentation, suggested that a difference sufficient for detection is not large enough for grouping.

The present study aims at comparing the differences required for *detecting* an irregularity within a row of dots or circles as opposed to perceiving these same stimuli as *grouped*. One may argue that the grouping threshold is based on a rather subjective criterion. However, the fact that the results are consistent among observers (see below) suggests that this criterion is based on structural constraints of our perception.

Three experiments were performed using distance (i.e., proximity), size (similarity) and luminance (similarity) as independent stimulus variables.

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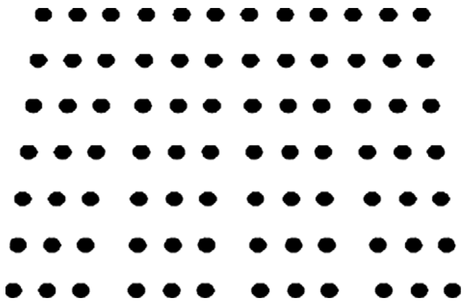

Fig. 1. Stimulus patterns selected from the set of 30 used in Experiment 1 with a progressively increasing size of spacing between triplets of dots. Each individual row represents a stimulus. Stimuli were presented in random order.

2. Experiment 1: spacing

Here, we presented a row of equally spaced dots whose spacing was then gradually increased at given locations. The aim was to determine the increase in gap size at which the dots (i) appeared to be non-uniformly distributed (detection threshold) as opposed to (ii) forming discrete ‘‘chunks” (grouping threshold).

2.1. Materials and methods

2.1.1. Subjects

Three subjects (mean age 32 years, SD = 2.3) participated in the experiment. All had normal or corrected-to-normal visual acuity.

2.1.2. Stimuli

Every stimulus pattern consisted of a horizontal row of 12 black dots on a white background. Dot diameter was 27.5 arcmin, dot luminance 3 cd/m^2 and background luminance 136 cd/m^2 (Michelson contrast = 95.7%). The standard distance between individual dots from contour to contour was 34.38 arcmin. For threshold measurements, the distance after the 3rd, 6th, and 9th dot was uniformly increased in steps of 1.27 arcmin, producing an ever-greater gap in these locations. There were 30 such stimuli with gap size ranging from 34.38 to 71 arcmin. Fig. 1 shows seven rows of dots out of a total of 30 with the spacing between triplets becoming progressively larger. Equi-spaced stimuli (first row) were used for catch trials.

2.1.3. Procedure

Subjects were seated 50 cm away from a CRT monitor, controlled by a Sony Vaio laptop VGN-NR21E/S. A chinrest was used to stabilize the head; fixation was binocular in the center of the display slightly below each row. Each stimulus was composed of a single row of dots and presented in random order for 1 s. Prior to the experiment, subjects were familiarized with the stimuli and procedure. They were instructed to respond by using either a detection or a grouping criterion. The detection task consisted of a Yes/No response, depending on whether or not they saw an irregularity in spacing within the row of 12 dots. Alternatively, in the grouping task, they responded whether or not they perceived the dots as grouped. Subjects responded by pressing different keys on the keyboard. The two tasks were randomly intermingled as were the stimuli. Measurements were repeated five times for each stimulus in both tasks, resulting in a total of 300 trials for each subject.

2.2. Results

All subjects reported that they found the task easy. We fitted our data, cumulated over three subjects, with a logistic function. The upper bound was set to 1 and the lower bound to $y_0 = 0$. $y = 0$ means that the stimulus never achieved detection or grouping, and $y = 1$ that, at a given spacing, the stimulus was always detected or seen as grouped. The only free parameters of the function are therefore b (the function slope) and t (the threshold). The resulting logistic function (similar to the one used by Gori, Giora, & Pedersini, 2008) is

$$Y = \frac{1}{1 + e^{-b*(x-t)}} \quad (1)$$

In this equation, x is the spacing between triplets in each row minus the standard distance between individual dots (i.e., the spacing increment), y the relative response frequency and e Euler's number.

In Fig. 2a, relative response frequency for three subjects is plotted as a function of the enlarged gap size minus the standard distance (i.e., spacing increment). The left curve (black) is the fitted function for the detection of an irregularity in spacing and the right curve (dashed gray) the fitted function for the perception of grouping[1]. The 50% threshold for detection corresponds to a difference in gap size of 2.5 arcmin, whereas the threshold for grouping equals 13 arcmin. The resulting ratio is 5.20. The difference between the two kinds of thresholds is statistically significant ($t_{(2)} = -20$, $p = .002$ for paired-samples t-test).

Fig. 2b illustrates the two stimulus patterns representing the detection (top) and grouping threshold (bottom), respectively. There was not a single ‘‘yes” response in the detection task, when the dots were equi-spaced, suggesting that false alarms may be disregarded. The same applies to Experiments 2–4.

Fig. 2c shows the results for each of the three subjects. The agreement is quite good.

2.3. Discussion

The large difference between the two kinds of thresholds for detection and grouping demonstrates that a mere irregularity in spacing is not sufficient to perceptually group dots according to the Gestalt factor of proximity. For grouping, the gap size has to be approximately five times larger than for detection. In order to test whether a similar relationship between detection and grouping thresholds holds for other stimulus parameters, the second experiment studied grouping according to the Gestalt factor of similarity.

3. Experiment 2: size

In this experiment, we presented rows of equi-spaced empty circles whose diameter was progressively increased within every other triplet. The spacing between circles remained the same. The aim was to determine the increase in diameter at which the enlarged circles (i) were seen as different in size (detection threshold) as opposed to (ii) forming triplets of circles (grouping threshold).

3.1. Materials and methods

3.1.1. Subjects

The same three subjects as in Experiment 1 participated in this study.

[1] The fitting details for detection are: $R^2 = .99$, $b = 0.98$, $t = 2.5$; for grouping: $R^2 = .99$, $b = 0.98$, $t = 13$.

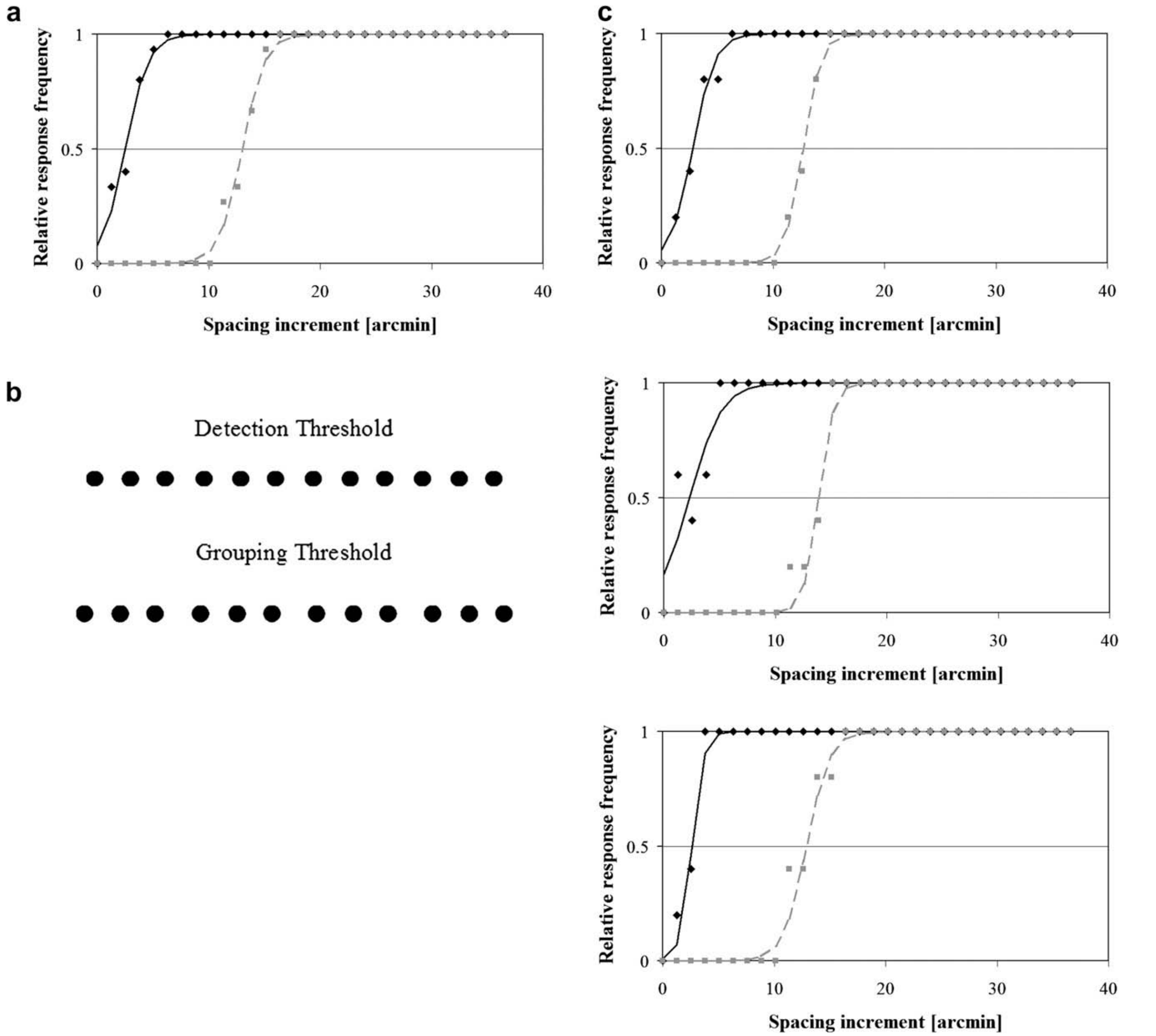

Fig. 2. Spacing: (a) relative response frequency for detection (diamonds) and grouping (squares) for three subjects plotted as a function of gap size between triplets of dots minus the standard distance. Data were fitted with a logistic function. ($N = 15$ measurements/condition). (b) Stimuli representing the detection and grouping thresholds, respectively. (c) Data for the three individual subjects.

3.1.2. Stimuli

The standard stimulus consisted of a horizontal row of 12 circles on a white background. Circles had a diameter of 27.5 arcmin and were equally spaced by 82.5 arcmin. The luminance of the contour was the same as for the dots in Experiment 1, and so was the luminance of the background. For testing, the diameter of the circles in the second and fourth triplet was increased in steps of 0.27 arcmin, while the size of the circles in the first and third triplet remained the same. The full experimental set consisted of 30 stimuli, ranging from 27.5 to 35.48 arcmin in diameter. Empty circles instead of filled dots were chosen to keep the perceptual ''salience'' of the elements within the row approximately equal. Furthermore, a larger separation between circles as opposed to dots (in Experiment 1) was used, to keep the effect of enlarging the diameter on perceived gap size small. Fig. 3 shows seven rows of circles out of a total of 30 with the difference in size of the circles between triplets progressively increasing.

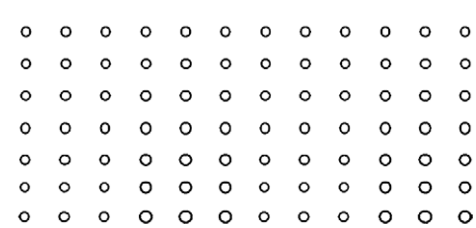

Fig. 3. Stimulus patterns selected from the set of 30 used in Experiment 2 with a progressively increasing difference in diameter between triplets of circles. Each row represents a stimulus.

3.1.3. Procedure

The procedure was the same as in the previous experiment, the only difference being the independent variable, size.

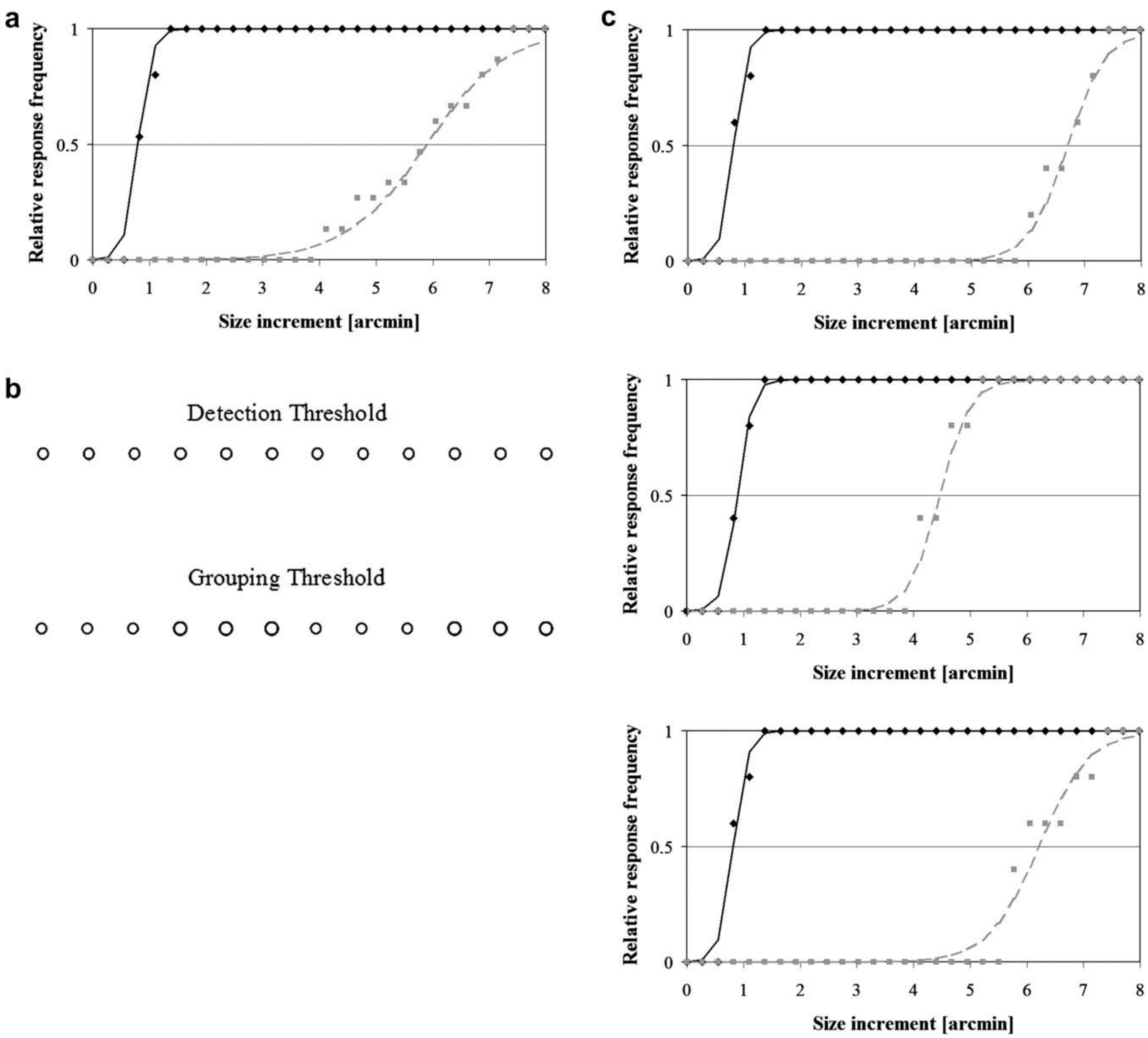

Fig. 4. Size: (a) relative response frequency for detection (diamonds) and grouping (squares) for three subjects plotted as a function of the diameter of the circles within the second and fourth triplet minus the standard size. (N = 15 measurements/condition). (b) Stimuli representing the detection and grouping threshold, respectively. (c) Data for the three individual subjects.

3.2. Results

Fig. 4a shows relative response frequency for three subjects plotted as a function of size of the enlarged circles minus the standard size of the circles (i.e., size increment). We fitted our data with the same logistic function[2] used in Experiment 1. The detection threshold is 0.8 arcmin, while the grouping threshold is 5.9 arcmin. The resulting ratio is 7.4. As in Experiment 1, the difference between the two kinds of thresholds is statistically significant ($t_{(2)} = -7.02$, $p = .02$ for paired-samples t-test).

Fig. 4b illustrates the two stimulus patterns representing the detection (top) and grouping threshold (bottom), respectively.

Fig. 4c shows the results for each of the three subjects. Notice that for subjects 1 and 3 the difference between the two kinds of curves was somewhat larger than for subject 2. Also, the slope of the grouping curve was flatter (see Fig. 5).

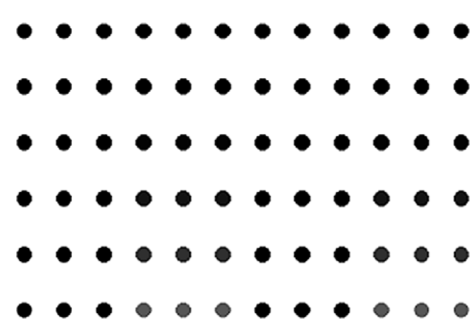

Fig. 5. Stimulus patterns selected from the set of 21 used in Experiment 3 with a progressively increasing difference in luminance between triplets of dots. Each row represents a stimulus. Brightness differences may not show due to printing.

3.3. Discussion

The difference between the two kinds of thresholds demonstrates that perceptual grouping according to the Gestalt factor of

[2] The fitting details for detection are: $R^2 = .99$, $b = 0.84$, $t = 0.8$; for grouping: $R^2 = .99$, $b = 1.39$, $t = 5.9$.

similarity requires an increase in size of the circles more than seven times larger than for detection. This prompted us to test yet another stimulus variable, luminance. This variable differs from the other two inasmuch as it does not pertain to the geometry of the stimulus pattern.

4. Experiment 3: luminance

In this experiment, we presented rows of equi-spaced dots whose luminance was progressively increased within every other triplet. The aim was to determine the increase in luminance at which the difference in brightness could (i) just be seen (detection threshold) as opposed to (ii) forming triplets of dots (grouping threshold).

4.1. Materials and methods

4.1.1. Subjects

The same three subjects as before participated as observers.

4.1.2. Stimuli

Every stimulus consisted of a row of 12 equi-spaced dots on a white background. The diameter and spacing of the dots as well as the standard luminance of the dots and background were the same as in Experiment 1. The full experimental set consisted of 21 stimuli. In each row the luminance of the dots in the second and fourth triplet was increased in steps of 0.3 cd/m^2, while in the first and third triplet it remained constant. The luminance of the lower-contrast dots ranged from 3 cd/m^2 to 18.7 cd/m^2 (Michelson contrast = 95.7–75.8%). Fig. 7 shows seven stimuli out of 21 with the difference in luminance between triplets progressively increasing.

4.1.3. Procedure

The procedure was the same as in the previous experiments, the only difference being the independent variable, luminance. There were 210 trials.

4.2. Results

Fig. 6a plots relative response frequency for three subjects as a function of luminance of the lower-contrast dots minus the standard luminance (i.e., luminance increment). The two curves refer to detection and grouping, respectively. Data were fitted with the same logistic function[3] used in Experiment 1. The detection threshold is 0.79 cd/m^2, while the grouping threshold is 5.1 cd/m^2. The resulting ratio is 6.6. The difference between the two kinds of threshold is again statistically significant ($t_{(2)} = -7.77$, $p = .016$ for paired-samples *t*-test).

Fig. 6b illustrates the two stimulus patterns representing the detection (top) and grouping threshold (bottom), respectively.

Fig. 6c shows good agreement between the results for each of the three subjects.

4.3. Discussion

The difference between thresholds for detection and grouping clearly shows that a difference in brightness between the dots is detected long before it results in a percept of grouping. The required increment is over six times larger than for detection. This again demonstrates that detection is not sufficient for grouping according to the Gestalt factor of similarity, even for a non-geometric stimulus variable such as luminance.

At this point the question arises, whether the difference in threshold is due to the fact that for a detection response one need only see any "irregularity" in the row of elements, whereas for a grouping response one must perceive three "irregularities" in certain fixed places. This would imply different amounts of information required for the different tasks and could therefore account for the large threshold difference observed.

5. Experiment 4: gap number

In order to test this hypothesis, we repeated Experiment 1 by reducing in each row of dots the number of triplets from 4 to 3 and the number of gaps from 3 to 2. If the large difference between the two kinds of thresholds had arisen predominantly from the circumstance that detection of a change in spacing requires seeing only a single enlarged gap, whereas perceptual grouping requires seeing all three, then we should obtain a significantly smaller difference between grouping and detection thresholds in this control experiment. If, however, the difference between the two kinds of thresholds were unrelated to the number of perceived gaps, but rather constituted a fundamental property of two qualitatively different processes, then the difference between thresholds should be similar to what we obtained in Experiment 1.

5.1. Materials and methods

5.1.1. Subjects

The same three subjects as before participated as observers.

5.1.2. Stimuli

All stimulus characteristics were equal to the stimuli used in Experiment 1, except for the smaller number of dots (9) and gaps (2 instead of 3). For threshold measurements, gap size after the 3rd and 6th dot was progressively increased by increments of 1.27 arcmin as before. The number of trials was 300 as in Experiment 1.

5.1.3. Procedure

The procedure was exactly the same as in Experiment 1.

5.2. Results

In Fig. 7a relative response frequency for three subjects is plotted as a function of the spacing increment. The two curves refer to detection and grouping, respectively. We fitted our data with the same logistic function[4] used in Experiment 1. The detection threshold is 2.98 arcmin (Experiment 1 = 2.5), whereas the threshold for grouping is 13.72 arcmin (Experiment 1 = 13). The resulting ratio is 4.6 (Experiment 1 = 5.2). The difference between the new detection and grouping thresholds is again statistically significant ($t_{(2)} = -12.43$, $p = .006$ for paired-samples *t*-test). On the other hand, a comparison of the results of Experiments 1 and 4 shows no significant difference between the values for the two thresholds ($t_{(2)} = -0.02$, $p = .984$ for paired-samples *t*-test) or the resulting ratios ($t_{(2)} = -0.96$, $p = .44$ for paired-samples *t*-test).

Fig. 7b illustrates the two stimuli representing the detection (top) and grouping threshold (bottom), respectively.

[3] The fitting details for detection are: $R^2 = .99$, $b = 14.84$, $t = 0.79$; for grouping: $R^2 = .99$, $b = 1.56$, $t = 5.1$.

[4] The fitting details for detection are: $R^2 = .99$, $b = 1.13$, $t = 2.98$; for grouping: $R^2 = .99$, $b = 0.86$, $t = 13.72$.

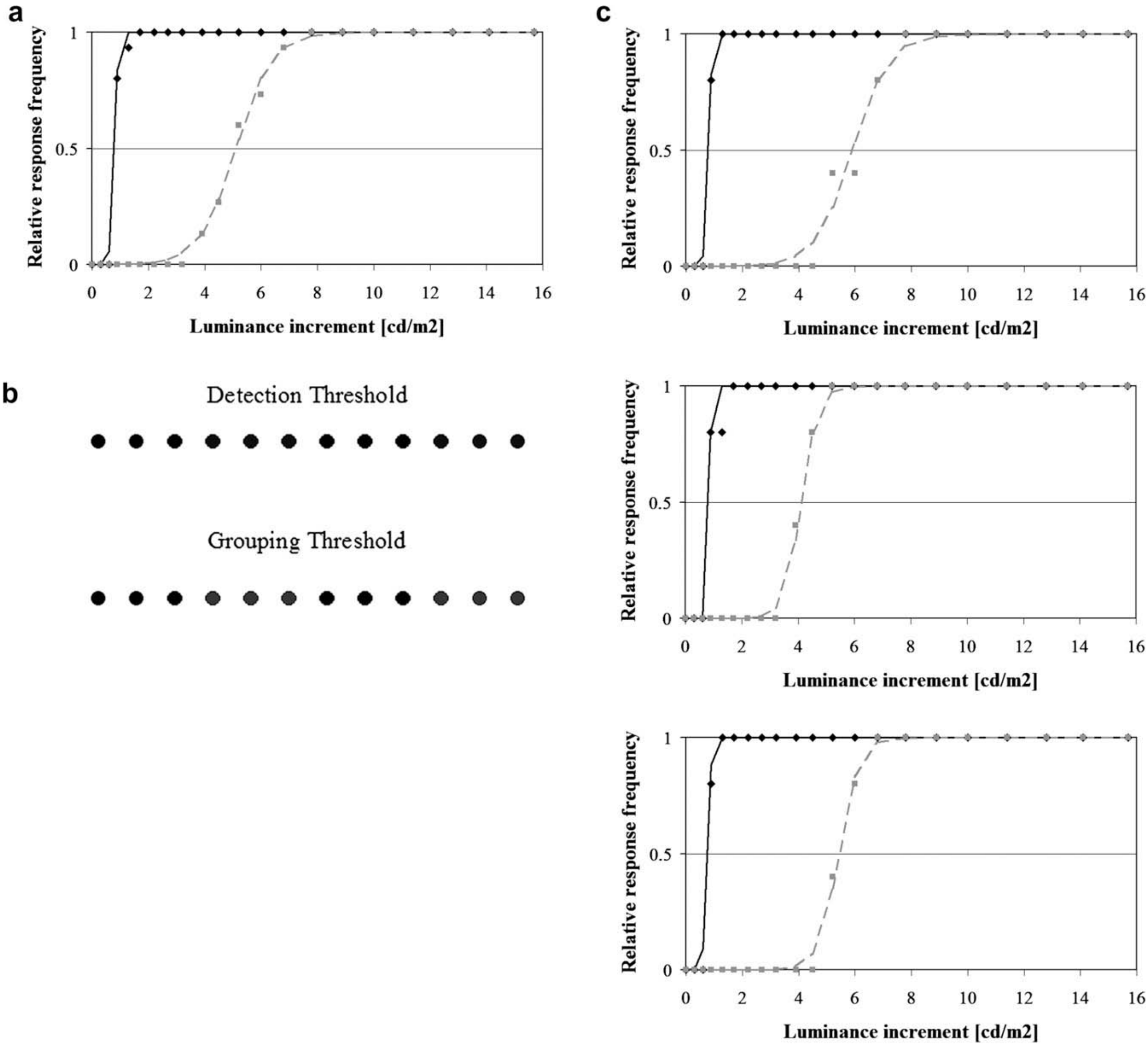

Fig. 6. Luminance: (a) relative response frequency for detection (diamonds) and grouping (squares) for three subjects plotted as a function of luminance of the dots within the second and fourth triplet minus the standard luminance. ($N = 15$ measurements/condition). (b) Stimuli representing the detection and grouping threshold for brightness, respectively. Brightness differences may not show due to printing. (c) Data for the three individual subjects.

5.3. Discussion

The comparison between the results of Experiments 1 and 4 shows that there is no significant difference, when the number of gaps in the stimulus is reduced from 3 to 2. This finding is inconsistent with the hypothesis that the observed difference between detection and grouping thresholds is attributable to different amounts of information required by the two response criteria. It rather points towards a fundamental difference, the former being a criterion pertaining to a sensory performance limit, the latter a criterion based on structural constraints of visual perception.

There is one more *caveat*. Because the stimulus manipulation occurred always in the same place within each row, subjects knew in advance where to look for to detect irregularities (in spacing, size, and luminance). This might have facilitated the detection relative to the grouping task. Therefore, another control experiment was performed.

6. Experiment 5: variable gap position

In order to test whether the observed difference between detection and grouping thresholds can be attributed, e.g., to the fixed gap position (in Experiment 1), we randomized the position of the gaps within the row of dots. If the large difference between the two kinds of thresholds had arisen mainly from the circumstance that fixed gap positions constitute local cues and thereby favor detection of non-uniformity over grouping, we would expect the detection threshold to be significantly higher in this control experiment. As a consequence, the difference between the two kinds of thresholds should become smaller. If, however, the detection threshold were unrelated to gap position, the difference should be similar to what we obtained in Experiment 1. Fixed gap position could conceivably also favor the grouping threshold, making it easier for subjects to perceptually structure the row of elements. If so, randomization of gap position resulting in groups

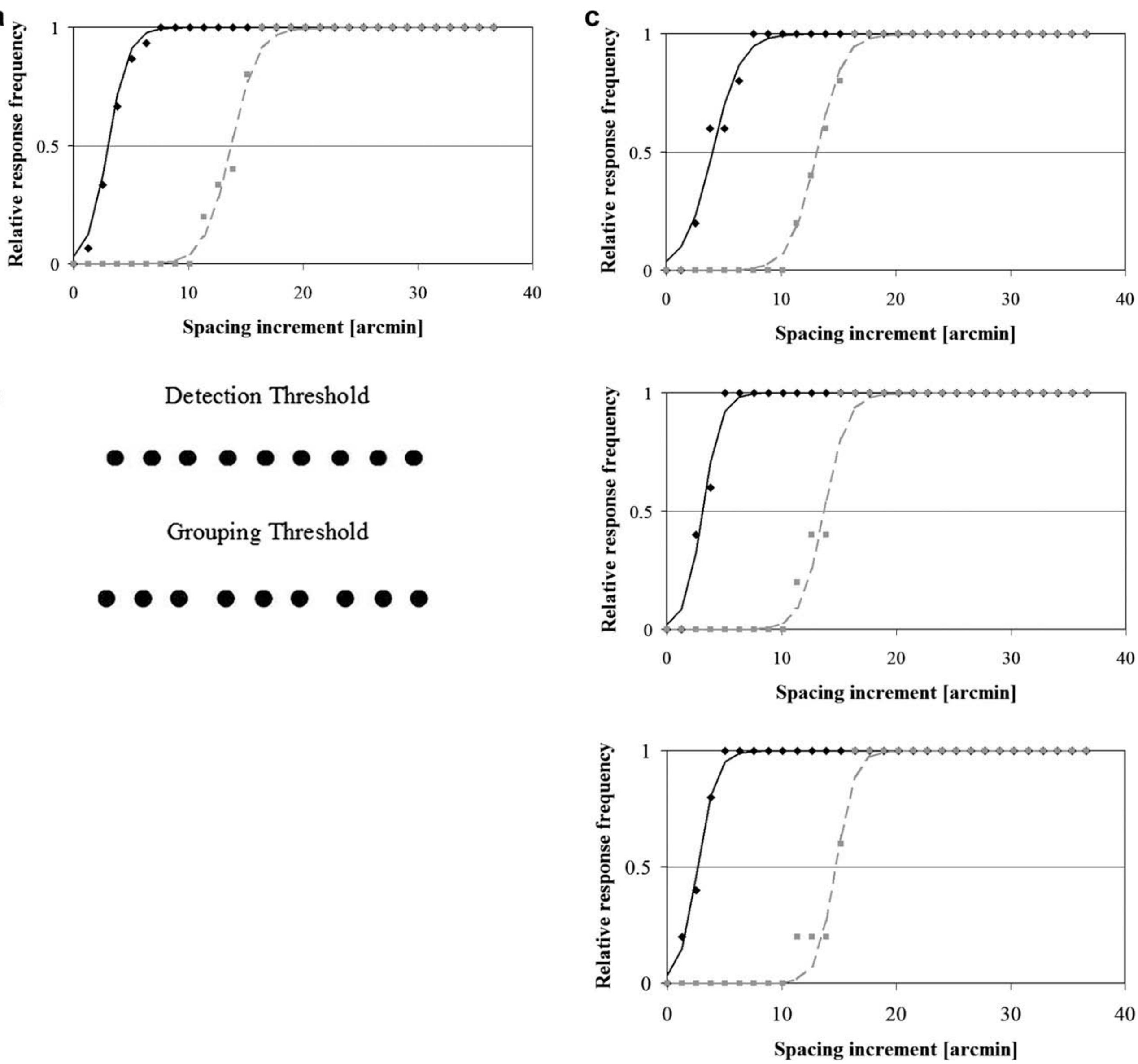

Fig. 7. Spacing. Three triplets only: (a) relative response frequency for detection (diamonds) and grouping (squares) for three subjects plotted as a function of the separation between triplets of dots minus the standard distance. (N = 15 measurements/condition). (b) Stimuli representing the detection and grouping threshold, respectively. (c) Data plotted for the three individual subjects.

of different size might be expected to elevate the grouping threshold. Again, no effect would suggest that grouping is unrelated to gap position and the difference between the two kinds of threshold should remain unchanged.

6.1. Materials and methods

6.1.1. Subjects

The same three subjects as before participated as observers.

6.1.2. Stimuli

All stimulus parameters were equal to the stimuli used in Experiment 4 except for gap position, which was randomized. There were two constraints: (i) the number of gaps was always two and (ii) group size ranged from two to five dots. This range was chosen to prevent the grouping task from becoming a search task. Gap size ranged from 34.38 to 58.37 arcmin in increment steps of 1.27 arcmin. The number of stimuli was 200 (10 gap positions $\times$ 20 gap sizes).

6.1.3. Procedure

The procedure was essentially the same as in Experiment 1. However, stimuli were repeated only three times (instead of five). Also, the number of trials was 1200 (instead of 300). Furthermore, to rule out guessing, subjects were required to indicate the position of the enlarged gaps after each detection trial; if incorrect, the trial was considered a false alarm.

6.2. Results

Fig. 8 shows relative response frequency for three subjects plotted as a function of the spacing increment. The two curves refer to detection and grouping, respectively. We fitted our data with the same logistic function[5] used in Experiment 1. The detection threshold is 2.4 arcmin (Experiment 1: 2.5), whereas the threshold for grouping

[5] The fitting details for detection are: R^2 = .99, b = 1.61, t = 2.4; for grouping: R^2 = .99, b = 0.64, t = 14.2.

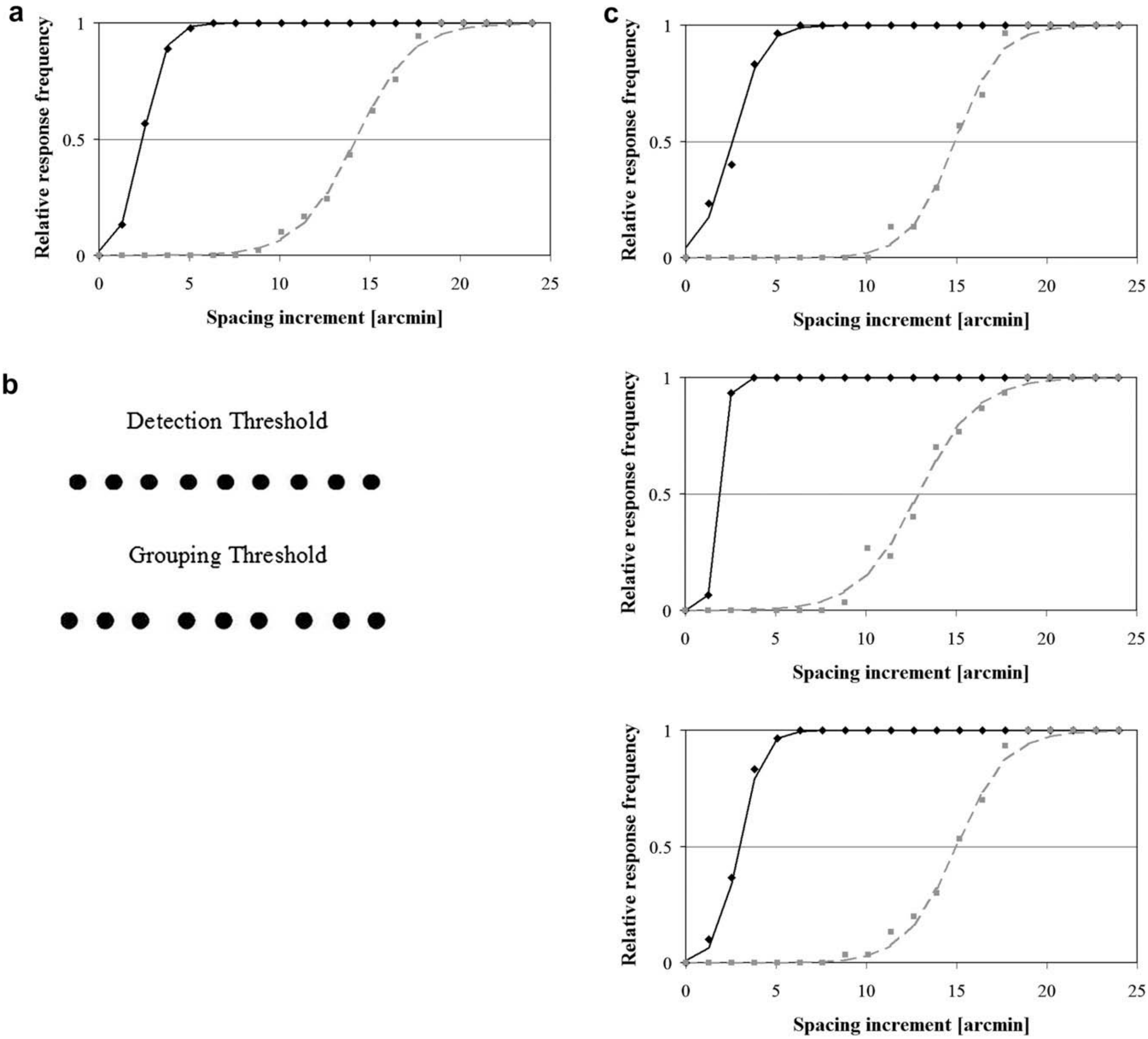

Fig. 8. Spacing. Two gaps only with randomized positions: (a) relative response frequency for detection (diamonds) and grouping (squares) for three subjects plotted as a function of separation between triplets of dots minus the standard distance. (N = 90 measurements/condition). (b) Stimuli representing the detection and grouping threshold, respectively. (c) Data plotted for the three individual subjects.

is 14.2 arcmin (Experiment 1: 13). The resulting ratio is 5.91 (Experiment 1: 5.2). The difference between the two kinds of thresholds is statistically significant ($t_{(2)} = -29.23$, $p = .001$ for paired-samples t-test). The results did not differ from those obtained in Experiment 1 for the threshold difference ($t_{(2)} = -1.29$, $p = .325$ for paired-samples t-test) and resulting ratio ($t_{(2)} = -2.74$, $p = .11$ for paired-samples t-test). Fig. 8b illustrates the two stimulus patterns representing the detection (top) and grouping threshold (bottom), respectively. The number of false alarms in the detection task was less than 1%.

6.3. Discussion

The comparison between the results of Experiments 1 and 5 shows that there is no significant difference. Therefore, the observed difference in threshold between detection and grouping cannot be attributed to the fixed gap positions, but rather points towards a fundamental difference between the two tasks. The fact that we found a small number of false alarms when subjects were required to specify the location of the gap strengthens the reliability of our measurements.

7. General discussion and conclusions

The results obtained in this study demonstrate that detection of a non-uniformity between elements that are otherwise equally arranged does not yet produce a perception of grouping. Regardless of the stimulus variable tested (spacing, diameter, luminance), grouping occurred when the difference was about 5–7 times larger than for detection. Any hypothesis based on the assumption that detection of an irregularity is a sufficient condition for grouping, is not supported by the data. Furthermore, the two control experiments make it highly unlikely that the difference in threshold comes about because more information is required for grouping than for detection (Experiment 4); and because fixed gap position favors detection over grouping (Experiment 5).

At this point the question is: what is needed, in addition to detection, to perceive grouping? A plausible answer is: a structured Gestalt. Grouping is an emergent property in a non-uniform sample that sets elements with common features perceptually apart from a mere aggregation. To achieve this, the visual system must organize the stimulus ("whole") from a multitude of elements to assemblies ("sub-wholes").

What could be the neuronal mechanisms responsible for these two percepts? Conceivably, two kinds of receptive field organization, scaled appropriately, might underlie the two kinds of thresholds. For example, small receptive fields in area V1 (for detection) vs. larger receptive fields in higher visual areas (for grouping) may account for the difference (Yazdanbakhsh & Gori, 2008). Another possibility is response synchronization, giving rise to binding and perceptual grouping (Gray, König, Engel, & Singer, 1989), as opposed to a local mechanism underlying detection. Experimental studies in monkey have confirmed that spatially separated neurons exhibit synchronized responses, when stimuli appear grouped in human perception (Brosch, Bauer, & Eckhorn, 1997; Castelo-Branco, Goebel, Neuenschwander, & Singer, 2000; Golledge et al., 2003; Livingstone, 1996). However, the evidence remains incomplete and controversial (Palanca & DeAngelis, 2005).

The quantification of the threshold difference necessary to perceive grouping as opposed to mere detection of a non-uniformity within an otherwise homogenous sample provides a starting point for future studies on the psychophysics of Gestalten.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.visres.2010.03.022.

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