The effects of structural information on perceived numerosity in two-dimensional object distributions

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Abstract
What factors influence our perception of numerosity under conditions such that we cannot simply use counting?

In this contribution we present evidence that perceived numerosity of a two-dimensional arrangement of dot-like items can be strongly affected by the presence of additional, structural information. Subjects estimated and adjusted the number of items in pairs of simultaneously presented stimuli. Three experiments were conducted with displayed numerosity of dot-like items as the controlled variable and line-polygons as structural information. In all three experiments we found a significant underestimation effect whose strength depended on the positioning of the polygon edges. While in Experiment 1 the positioning of polygon edges between dots (i.e. joined dots) resulted in a strong numerosity underestimation, the simple presence of polygon structures even with no grouping function gave a less intense underestimation effect in Experiment 2. Employing an eyetracker-device in a third experiment to obtain eye-movement data, additional insight into visual attentiveness processes during numerosity comparison tasks could be gained to help to explain the observed behaviour.

1 Introduction
The rapid judgement of the numerosity of items in a visual display without resorting to serial counting is an important perceptual capability. In this contribution we investigate how this perceptual capability is affected by the presence of additional structural information in the display.

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To date, no more detailed examinations have been carried out with regard to this dependency and the employment of this type of structural information in particular. Specifically, we consider the perception of numerosity in two-dimensional arrangements of dot-like stimuli and present evidence that additional structural information in the form of line segments added to the display results in a marked underestimation effect whose strength varies with the positioning of the line segments relative to the dot-items.

The present study extends previous research on the effect of perceptual grouping and structural information on numerosity estimations that has always been an interesting research topic for psychologists. Up to now, different kinds of structures were used. Apart from Messenger (Messenger, 1904), most research has been done when structuring/clustering was achieved by either the positioning of items or item-inherent features instead of adding extra structures. In detail, the effects of variations of features such as object density, object distribution or “cluster intensity”, numerosity, and distance between items were investigated while the effects of lines and polygons as structural information were little explored. The findings of the early research are summarized below.

According to Klahr and Wallace (Klahr and Wallace, 1976), a “pattern recognition” process occurs in three successive phases in perception tasks involving numerosity estimations: subitizing, unpacking, estimating. The idea of subitizing, i.e. the clustering of patterns, implies an influence of figural arrangements on perception processes. As demonstrated by Simons and Langheinrich (Simons and Langheinrich, 1982), figural aspects such as

- alternatives for subitizing and unpacking,
- the presence of a singular structure with no significant substructures, and
- the ambiguity of single items in relation to their belonging to a certain (sub)structure

prevent rapid subitizing and unpacking.

Numerosity estimations of “regular” patterns take less time than those of “random” distributions of items. However, there is also an exception: linear or suggestive (figural) arrangements take longer (Warren, 1897).

Even more interesting were experiments primarily aimed at gaining more insight into the influence of stimulus conditions on numerosity estimation. Ginsburg, for example, observed what he called the “regular-random-illusion” (Ginsburg, 1991): regular patterns were usually overestimated, random object distributions rather underestimated instead, with the perceptual numerosity decreasing as the arrangement changed from regular towards random towards clustered (Watler, 1984). Furthermore, numerosity estimation accuracy decreased when the number of items displayed was increased.

Another dependency was found by Krueger, who established that more loosely spaced dots appear more numerous than the same dots spaced more densely (Krueger, 1972). The author offered no proper explanation, but the correspondence between his findings and Binet’s early results (Binet, 1890; Pollack and Brenner, 1969) — Binet came to similar conclusions as early as 1890 — is obvious.
Regarding the interpretations of the dependencies in Ginsburg's experiments, the explanations were based upon Gestalt-theoretical approaches by Frith and Frith (Frith and Frith, 1972): a set of items arranged so as to form a good “figure” will appear more numerous: “solitaire illusion”. If one grants that the regular stimulus is the best figure, then the higher estimates for the numerosity of the regular pattern would fit in with such a view. The contradictory use of Gestalt-theoretical concepts in comparison with Taves’ approach (Taves, 1941) demonstrates that informal perceptual theories like those of the Gestaltists cannot account for various manifestations of interaction between spatial arrangements and numerosity. Taves found that under conditions of short inspection a regular (i.e. circular or linear) arrangement of 20 dots is regarded as being less numerous than a cluster of 20 more or less randomly positioned dots.

Other attempts to explain behaviour during numerosity estimation tasks include the poles-of-intention-, the area-, and the contrast-with-expectancy-approaches.

**Poles of intention:** It was suggested by Brunswik (Brunswik, 1934) that perceptual judgements are sometimes a compromise between two poles of intention, a conscious one and a latent one. In this case, the conscious pole is set by the instructions — to respond to the number of dots. When the dot pattern appears to break up into a number of separate clusters, this may induce a latent pole of intention to respond to the number of those clusters. Of the two poles, the conscious one is more heavily weighted.

**Area:** Binet (Binet, 1890) was the first to call attention to the area covered as a factor affecting perceived numerosity (see above). However, occupied area can be interpreted in at least three different ways: (a) in the narrowest, or literal, sense as the total area of the items themselves (Ginsburg and Nicholls, 1988); (b) in the broadest sense, as the area covered by the pattern as a whole, for instance the area in a convex hull; and (c) in an intermediate sense as described by Vos et al (Vos et al, 1988): “a filled area, which is roughly the impressionistic ensemble of parts of the stimulus field occupied by the dots.”

**Contrast with expectancy:** Birnbaum and Veit (Birnbaum and Veit, 1973) suggested that some judgemental illusions may reflect a contrast to expectancies based on prior experience. “Naturally occurring objects like trees in a forest tend to be distributed in clusters. These objects tend to occur in large numbers. Contrasted with this are small groups of items artificially positioned in regular arrangements, like eggs in a carton, or the dots on a dice.” (Ginsburg and Goldstein, 1987). Thus a higher standard is created for high-cluster sets than for regular patterns, and therefore the former will be judged to be less numerous.

In contrast to previous research, the present paper is concerned with the effect of additional structural information on perceived numerosity in comparison tasks. Explanations for the observed responses in such tasks take into account the interpretation attempts introduced above. Whereas the scenario is dynamic in Experiments 1 and 2, Experiment 3 presents a static one. This means that in the first two experiments subjects have to adjust the number of items in the dots-only image as to perceive equal numerosity of dots in both hemifields while the experimental setup of Experiment 3 only requires a simple (binary) decision in which hemifield of the stimulus more items are displayed.
The subsequent sections of this paper describe the experiments in detail, show the findings and propose explanations of the results, incorporating the eye-movement data obtained in Experiment 3 as indicators for visual attentiveness. Whereas the structural information presented in Experiment 1 has a strong grouping function, Experiment 2 was designed to study the effects of structural information with no such grouping function on perceived numerosity.

2 Experiment 1

2.1 Method

2.1.1 Subjects

The subjects were 25 experimentally naive students in different classes; 16 males and 9 females. Their average age was 27.3 years. The subjects were paid for their participation in the experiment.

2.1.2 Stimuli

A set of 28 configurations of dots, split into 7 subsets, was constructed. A subset consisted of 30, 50, 70, 90, 110, 130, or 150 dots respectively. Dots were randomly positioned and equally distributed, keeping a minimum distance of 9 pixels (visual angle: 0.4°) between centers of neighbouring dots. Dots were of circular shape with a diameter of 4 pixels (visual angle: 0.18°) and colour “red”, (R, G, B)=(255, 0, 0). By linking every 2, 3, 4, 10, 20, or 30 dots of each of the 28 configurations by lines as to form polygons, plus the 28 original configurations with no links, a total number of 196 “structured images” was generated. The original configurations, in fact presenting unstructured/unclustered stimuli (cluster size 1), were included in order to obtain “baseline”-data for the estimations. Polygons were generated so that no overlapping of structures occurred and clusters were perfectly separable. The dots in a group were joined by lines so as to follow the shortest possible path (“Traveling Salesman Problem”). All clusters in a structured image were of the same size. Exception: the size of the “last” cluster was always determined by the remaining dots and might thus be smaller. Polygon lines’ width was 1 pixel (visual angle: 0.04°).

Independent of the positions of dots in the structured images, 196 configurations of dots were constructed to form “unstructured images” used in the comparison experiment. 300 dots per configuration were generated throughout, a random number \( n \in [1, 300] \) of dots displayed with the initial scenario. Size, shape, and colour of dots were the same as those used in the structured images.

The stimuli were displayed in front of a black background on a computer monitor, 17-inch display diagonal. The monitor’s spatial resolution was set to 640x480 pixels. The maximum visual angle of either a structured or unstructured image measured up to 7.05° horizontally and 10.71° vertically.

Fig. 1 shows a sample stimulus used in this experiment.
2.1.3 Procedure

Each subject was presented with the entire set of 196 pairs of stimuli. The structured images were always displayed in the left, the unstructured images in the right hemifield of the screen, separated by a vertical line. Both images of such a pair were shown simultaneously. The distance between screen and subject measured approximately 80 cm with the computer monitor being located at eye-level.

The subjects were asked to adjust the number of dots in the unstructured image so as to display an equal number of dots in both hemifields — in the subjects’ judgement. The numerosity adjustment was implemented via computer mouse movements. Mouse movements were synchronised with the levelling of a virtual baseline, i.e. dots always appeared and vanished at the same positions in a predefined order. This setup prevented subjects from trying to reconstruct a pattern in order to simplify numerosity perception, estimation and adjustment.

No time-limit was imposed on the subjects, although the task was formulated “to adjust the number of items as quickly and accurately as possible”. The subjects did not get any feedback about their “score” during the experiment. On average, it took the subjects approximately 30 minutes to complete the experiment.

2.2 Results

As can be concluded from Fig. 2, the main result of the experiment is an obvious confirmation of the hypothesis formulated in the beginning: a numerosity underestimation caused by the structuring of item arrangements.  

Independent of cluster size, the underestimation can be observed for all numbers of

\footnote{As almost invisibly small sizes of errorbars in all experiments conducted demonstrate, data taken into account show low variances and highly significant results (Figs. 14 and 15).}
dots displayed. Both Figures 2 and 3 show all curves being entirely situated below the reference line. The reference line represents the curve for the unbiased adjustment, i.e. the number of dots estimated/adjusted is equivalent to that of dots given. Therefore, the relative number of dots estimated represents a measure for estimation bias. With 30 points given, the only exception of this underestimation tendency becomes visible for unclustered structured images (cluster size 1).

Another striking result is the increasing underestimation for higher numbers of dots given (Fig. 2) and towards larger clusters (Fig. 3). Curves in Fig. 2 show a gradual, approximately linear decline from 20% for 30 dots given down to 44% underestimation for 150 dots given on average. In Fig. 3, three different levels of estimation bias, dependent on cluster size, are apparent. Even unclustered images are usually underestimated by 4%, images with cluster sizes 2, 3, or 4 by 30%, and images with cluster sizes 10, 20, or 30 by 37%. In order to judge the significance of the dependency between cluster size and numerosity estimation, a one-factorial analysis of variance was conducted. The analysis confirmed the significance of the dependency between cluster size and relative number of dots estimated/adjusted ($F(6.4194) = 153.99; MSE = 0.0622; p < 0.0001$) and the differences amongst the three levels mentioned:

- For unclustered images (cluster size 1), significantly larger numbers of dots are adjusted than for cluster sizes 2, 3, and 4 (as a group) ($F(1.699) = 590.91; MSE = 0.0597; p < 0.0001$).
- For the latter group again significantly larger numbers of dots are adjusted than for cluster sizes 10, 20, and 30 (as a group) ($F(1.699) = 81.56; MSE = 0.0636; p < 0.0001$).
- The number of dots adjusted within either of the groups with cluster sizes 2 to 4 and 10 to 30 does not vary significantly.

Regarding the latter result, the assumption that images with cluster size 2 result in a special numerosity estimation effect has to be rejected — although a small “bump” in
the curves indicates some odd effect. Such an effect could have been presumed as — in contrast to all other cluster sizes — only half as many lines as dots are visible with this cluster size, causing the particularities in perceived numerosity.

Back to Fig. 2, even the curve for unclustered images also shows a rather unexpected, significant underestimation effect. With both images of such a pair consisting of dots only, a correct numerosity estimation should have been expected on average, so that the curve would approximate the reference line.

Later, temporal aspects were analysed, despite the vague instructions for subjects with regard to time limits during the experiment. The results obtained are summarized below:

- Mean duration for estimation/adjustment per trial: ca. 6 secs.
- No significant improvement of estimation quality with increasing adjustment times.
- As could be expected — due to the experimental setup with no feedback for subjects during the experiment — no improvement of estimation quality towards the end of the experiment.
- Longer adjustment times in the first third of the experiment (11 secs. in the very beginning), that, with approximately the 70th pair of images reaches an almost constant 5–6 secs. for estimation/adjustment.

3 Experiment 2

3.1 Method

3.1.1 Subjects

The subjects were 10 experimentally naive students in different classes; 7 males and 3 females. Their average age was 25.1 years. The subjects were paid for their participation in the experiment.

3.1.2 Stimuli

As before, the same set of 28 configurations of randomly positioned dots was used as a base for the stimuli generated in the left hemifield of the screen. Unlike linking dots directly to build polygons as to construct the total of 196 structured images, in this experiment the polygons’ corners were not directly placed on dots. Instead, the polygons were now randomly positioned among the dots. All polygons in a stimulus again had the same cluster size, the total number of polygons’ corners in a single image being equal to the number of dots in that hemifield. For better reference, the hemifield containing the polygons will still be called “structured image”, despite the lack of a grouping effect achieved by the arrangement in Experiment 1. The same cluster sizes were used as in Experiment 1, so that a total of 196 stimuli were generated again.

For the unstructured images in the right hemifield of the screen the previously constructed set was employed.

Fig. 4 shows a sample stimulus used in this experiment.
3.1.3 Procedure
The procedure was the same as in Experiment 1.

3.2 Results
Compared to the previous experiment, the results of Experiment 2 differ in many aspects. Despite the general underestimation effect which is still prominent, the effect is far less intense than before. With the curve for unclustered images (cluster size 1) being separated from the rest (Fig. 5) again, the given numbers of dots are underestimated by 20% only for all other numbers of dots given throughout. A gradual deterioration of estimation quality, i.e. relative number of dots given, is no longer visible.

Figure 5: Relative number of dots estimated (unstructured image) versus number of dots actually displayed (structured image) in Experiment 2

Figure 6: Relative number of dots estimated (unstructured image) versus cluster size in Experiment 2
As shown in Fig. 6, cluster size does not have a great impact on the estimation bias any more. No such different levels as in Fig. 3 are visible, but again unclustered images (cluster size 1) are underestimated by 4% on average, confirming the previous experiment's findings.

Regarding the analysis of temporal aspects, few differences between the two experiments can be found. The only two particularities of Experiment 2 are:

- mean duration for estimation/adjustment: 3–4 secs.
- no accustomization period visible, i.e. no longer duration for estimation/adjustment in the experiment’s beginning

4 Experiment 3

4.1 Method

4.1.1 Subjects

The subjects were 10 experimentally naive students in different classes; 5 males and 5 females. Their average age was 28.2 years. The subjects were paid for their participation in the experiment.

4.1.2 Apparatus

Unlike the previous experiments, this experiment recorded eye-movement data and was primarily aimed at gaining more insight into visual attentiveness during numerosity perception processes in comparison tasks. The eyetracker-device used is an SMI-Eyelink system, offering binocular eyetracking-facilities, on-line data-processing at a sampling rate of 250 Hz, and a gaze- and eye-position resolution of 0.005° with a gaze-position accuracy of 0.5°–1.0°.

4.1.3 Stimuli

The type of stimuli used in this experiment was the same as in Experiment 1, i.e. structural images (again presented in the left hemi-field of a computer screen) with either 30,
50, 70, 90, 110, 130, or 150 dots given and cluster sizes of 1, 2, 3, 4, 10, 20, or 30. The constructed polygons’ corners were positioned on the dots directly again as to achieve a grouping effect. With now 56 base dots-configurations being generated, a total stimuli set of 392 images, equally representing all possible combinations of dots given and cluster sizes, resulted. Due to a slightly different procedure (c.f. Section 4.1.4), numbers of dots in the unstructured images of stimulus-pairs were set to show \( m = n \pm 50\% \) dots, where \( n \) equals the number of dots given in the corresponding structured image and \( m \) is randomly chosen within the given range. The combination of structured and unstructured images to form a stimulus-pair is the same for all subjects in order to facilitate subsequent data-processing and to improve comparability of data/results.

### 4.1.4 Procedure

After an initialization and calibration procedure for the eyetracker-system, the subjects (wearing the eyetracker-helmet with the necessary devices to monitor pupil movement) were presented with the entire set of 392 pairs of stimuli. The subjects’ task was given as “to decide whether more dots are shown in the right or left hemifield”, i.e. to make a simple binary decision. A decision was confirmed by a subject’s pressing either the left or right button of a computer mouse respectively. Unlike before, a numerosity adjustment of dots was not required any longer. All other conditions of the experimental setup remained the same (c.f. Section 2.1.3).

### 4.2 Results

Analysed in a way analogous to Experiments 1 and 2, results confirmed — as could be expected — the findings of Experiment 1. Due to the modified experimental setup and procedure, data cannot directly be compared, but results allow for analogous statements with regard to the observed underestimation effects. However, it must be mentioned that, for unclustered images (cluster size 1), there was no longer a significant underestimation. The results indicate that the ratio of the “more dots in the left hemifield”-to the “more dots in the right hemifield”-decisions of subjects deviates from the real, correct ratio by \( 0.71\% \) only, i.e. neither a significant under- nor overestimation tendency can be found. With regards to the setup and procedure chosen in this experiment that means that, on average, only 0.4 stimuli per subject are incorrectly judged (compared to a total of 56 stimuli with cluster size 1 in the structured image given per person).

A more interesting aspect of this experiment was the analysis of the recorded eye-movement data. The following behaviour could be observed:

- More fixations occur in the structured than in the unstructured image (Figs. 9 and 11).
- The more dots are displayed, the longer fixations take (Fig. 10). The number of fixations does not increase with the number of dots (Fig. 9).
- With large numbers of dots/clusters being displayed, only some “prototypical” clusters are fixated. Large areas of the screen, in particular those off-center, “attract” little visual attentiveness and are only “scanned” peripherally.
- Neither the number of fixations nor the fixation duration varies significantly with cluster size. Exception: for cluster sizes of 1 and 2, significantly fewer fixations are made — compared to larger cluster sizes (Figs. 11 and 12).
Saccade length does not vary significantly either with the number of dots given or with cluster size, longer saccade length for cluster size 1 being the only exception.

In the structured image, the fixated objects are the clusters (as a whole) rather than single dots (Fig. 13, pto.). Only one or two fixation(s) per cluster are used.

In the unstructured image, areas with high object density are more frequently visited and fixations tend to occur in these areas (Fig. 13).

5 Discussion

A key result from the reported experiments is that a general underestimation effect for perceived numerosity can be observed, independently of the procedure and the type of stimuli presented. Nevertheless, the strength of this effect varies considerably with stimuli conditions. In particular, the unexpected presence of an underestimation effect even for single item “clusters” (cluster size 1) in Experiments 1 and 2 suggests that the experimental setup and procedure chosen also seem to have some impact on numerosity estimations. As a general pattern, valid for all cluster sizes investigated, we found that
Figure 13: A typical scan-path

the presence of additional structural information tends to significantly enhance the underestimation effect.

Due to the presence of structural information with a grouping function in Experiment 1, dots are no longer perceived as single items, but rather as clusters or groups, forming "figures". According to Brunswik's poles-of-intention-approach (Brunswik, 1934) both the numbers of dots (representing a "conscious" pole) and clusters ("unconscious" pole) should be taken into account for the numerosity estimation. The actual numerosity estimation being the mean value of the two poles, weighting the conscious one more heavily, the observed underestimation effect would be well in line with this interpretation (c.f. Section 1).

With an increasing number of dots, more clusters are generated — provided cluster size stays the same. Coinciding with the Gestaltists' theories (Frith and Frith, 1972) that for larger numbers of clusters the perception of "good" figures becomes more difficult, the decrease of estimation bias appears to be explicable for these conditions given.

Other plausible explanations were suggested by Ginsburg (Ginsburg, 1978 and 1991) and Watler (Watler, 1984). They introduced the notion of a dependency between "cluster ratio" and estimation bias, the cluster ratio labelling a position on a continuum of organization, ranging from "highly regular", through "random", to "clustered". Ginsburg and Watler found that with increasing randomness in item arrangements, a continuously increasing underestimation of perceived numerosity can be observed. As the present experiments demonstrate, the arrangements of dots do "naturally" change.
from fairly “regular” to “random”, to “clustered” when the number of dots given is increased.

Although Frith’s and Frith’s Gestaltist-approach seems to best explain the observed behaviour, it does not allow for a satisfactory explanation of a significantly stronger underestimation when large clusters and low numbers of dots are shown (compared to smaller cluster sizes). According to their approach, rather the contrary should be expected. Nevertheless, taking Taves’ (Taves, 1941) findings into account as well, Gestaltists’s theories still seem acceptable as explanatory attempts. Taves showed that a figure, even if it is supposed to be a “good” one in Frith’s and Frith’s terms, does rather evoke a lower impression of numerosity, provided that the figure’s basic pattern is either linear or circular. Stimuli used in the present experiments showed fairly circular shapes for those particular arrangements.

Furthermore, figural aspects account for larger differences in estimation biases for smaller numbers of dots given than for those where larger arrangements are presented: if the number of dots increases, figural aspects are continuously eliminated and the underestimation effect is only due to the arrangement’s randomness/irregularity (Ginsburg, 1980 and Ginsburg and Nicholls, 1988).

As for comparing unstructured images (i.e., each item forms a “cluster” of size 1), one might assume that the abovementioned explanations would account for the underestimation effect and its intensifying for larger arrangements of dots, too. But, as both images of a stimulus are presented simultaneously, this explanation does not hold. Instead, a possible impact of the experimental setup itself, the estimation, decision-making, and adjustment procedure in particular can be suspected. As Experiment 3 proved, no such significant underestimation effect occurs when a simple binary decision is required, replacing the more (cognitively) complex numerosity adjustment of Experiment 1. Without exploring these possibilities in depth, it can be assumed that subjects approach Experiment 1 “carefully”, rather giving a too low numerosity estimation than “risking” an overestimation. It can be speculated that this behaviour is due to some sort of a respecting attitude of subjects towards the technical apparatus or — alternatively — a fear of punishment in the case of an overestimation. This might result in “modesty”, i.e. underestimation. Finally, an accustomization effect could be assumed, originating from the fact that only every seventh stimulus is of this kind. However, such an effect should then also have been noticed in Experiment 3.

Having already interpreted the dependencies between cluster size and estimation bias, a few more aspects should be mentioned. Despite the roughly circular shape of clusters with size greater than ten, such a figure might, however, due to its low saliency, become incomprehensive. The range of so-called “magic numbers” is exceeded (again) and clusters themselves have to be subitized (Klahr and Wallace, 1976). This process obviously contributes to a further increase of estimation bias, i.e. intensified underestimation. Thereafter, estimation bias stays on the same level. In this context, magic numbers can be understood as the maximum number of dots that can be correctly judged with a single glance. The magic number varies dependent on stimuli-conditions. It was found to be four in Atkinson’s experiments (Atkinson et al, 1976). Earlier research by Sir Hamilton (Hamilton, 1859) and Jevons (Jevons, 1871) led to similar findings.
The results of Experiment 2 seem to prove the Gestaltists’ theories correct. Lacking the grouping-aid of Experiment 1, considerably weaker underestimation occurs. This is easily understood as no such figures with a direct relation/link to dots are constructed, creating the effects on perceived numerosity as discussed before. The underestimation tendency in this experiment seems to be only caused by the simple presence of structural information and a “naturally” achieved clustering due to random item arrangements. Maybe the estimation procedure itself again (experimental setup) also accounts for some of the effect.

In conclusion, numerosity estimations are to some extent influenced by the simple presence of additional (structural) information even with no grouping function (Experiment 2). The observed underestimation effect is intensified in case the inserted structures (polygons) support a perceptual grouping of the stimuli (Experiment 1). Figs. 14 and 15 combine and visualize the essential results of these two experiments. The size of errorbars underlines the high significance of the observed data.

Figure 14: Relative number of dots estimated (unstructured image) versus number of dots actually displayed (structured image)

Figure 15: Relative number of dots estimated (unstructured image) versus cluster size

The results of Experiment 3 lend additional support to the previously discussed interpretations. As eye-movement data shows, clusters are indeed perceived as a whole figure, using a single (or a maximum of two) fixation(s). Dots are usually not directly fixated in either hemifield. It can therefore be assumed that these perceived (cluster) numerosities are well reflected in the numerosity estimations, numbers of dots themselves only registered via extra-foveal processes (poles-of-intention approach). As fixation durations rise whereas numbers of fixations do not significantly increase for larger arrangements of dots, it must be assumed that subjects try to take in more information per fixation. For even larger arrangements and larger cluster numbers, this leads to prototypical fixations only and therefore to a heightened error in perceived numerosity. Subjects are obviously not capable of applying prototypical items to the whole arrangement, completely omitting to estimate some areas. The information acquired via extra-foveal vision and perception is not adequately reflected in cognitive processes/calculations, resulting in incorrect estimates for perceived numerosity.

With the results obtained through the experiments, some very interesting points could be established, contributing towards a better understanding of perceptive and
cognitive processes during comparison tasks with special emphasis on the impact of additional structural information on perceived numerosity. Perceived numerosity is one of the important general dimensions that aid us in forming rapid judgements about visual scenes. We have shown that this apparently “simple” ability can be significantly influenced by additional information in a way that — broadly speaking — “less” can appear as “more”. We hope that the results in the present paper can contribute to a better understanding of our perception of numerosity and provide a basis for developing more quantitative models that describe the observed data and link them to other levels of description such as computational or connectionist accounts of the underlying processes.

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