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Determinants of filled/empty optical illusion: Differential effects of patterning

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A subdivided path in the visual field appears longer than an empty path of the same length. This effect may be attributed to the division of the path into multiple segments, or to an influence of the visual elements used to mark the subdivision, and thus filling-up the estimated space. To address this question, we used two series of stimuli, in which the spatial distribution of the filling optical mater, or the form of the dividers, was varied while the relative coverage of the filled space was kept constant. We found significant dependence of the effect magnitude on a number of filling elements as well as on their form. These results indicate that the illusory space expansion is not merely an effect of "filling-up" the space, but it also depends on the filling pattern. Consequences of these findings for the theory of the Oppel–Kundt phenomenon are briefly discussed.

Key words: geometric–optical illusions, Oppel–Kundt phenomenon, optical matter, vision, visual space

INTRODUCTION

Geometric–optical illusions (GOI) is a covering term for a multitude of phenomena in which subjective perception of extents, angles or forms is affected by additional (contextual) elements present in the visual field. The term was coined by J.J. Oppel (1855), who also described a phenomenon now bearing his name: a spatial extent subdivided by a certain number of equally spaced markers is subjectively perceived as greater than the same undivided extent (Oppel 1861). This effect is usually demonstrated in simple line drawings (Fig. 1a,b) and is known as the "Oppel–Kundt illusion" (OKI) (Coren and Girgus 1978, Robinson 1998).

The OKI has been also called an "illusion of interrupted extent" (Sanford 1903, Luckiesh 1922, Metzger 1975), a name positing the subdivision of a given path or area in the visual field as the major factor in its illusory expansion (Fig. 1c,d). However, further research revealed the dependence of the effect not only on the number of the subdividing elements, but also on their appearance. For example, Spiegel (1937, p. 339f) found that shortening the dividers from linear segments to round dots reduced the effect magnitude, while increasing their width had no effect. Wackermann and Kastner (2009) observed that, using excessively long line segments as the subdividing elements, the illusory effect was reduced or vanished completely. In a follow-up study, Wackermann and Kastner (2010) demonstrated a non-monotonic functional dependence of the effect magnitude on the number of the dividers as well as on their extent. These findings indicate that the effect depends not only on the numerosity of the contextual elements in the visual field, but possibly also on their form and spatial distribution in the filled area (Fig. 1c–e); hence our preference for naming the phenomenon a "filled/empty (space) illusion" (Wackermann and Kastner 2009).

Variant namings of the same phenomenon, as well as experimental findings reported above, indicate some ambiguity concerning the primary cause of the OKI. Is it the effect of subdivision of a path into separate segments, as suggested in earlier literature, or an effect of filling-up the space between the delimiters of the given path? Additional visual markers are needed

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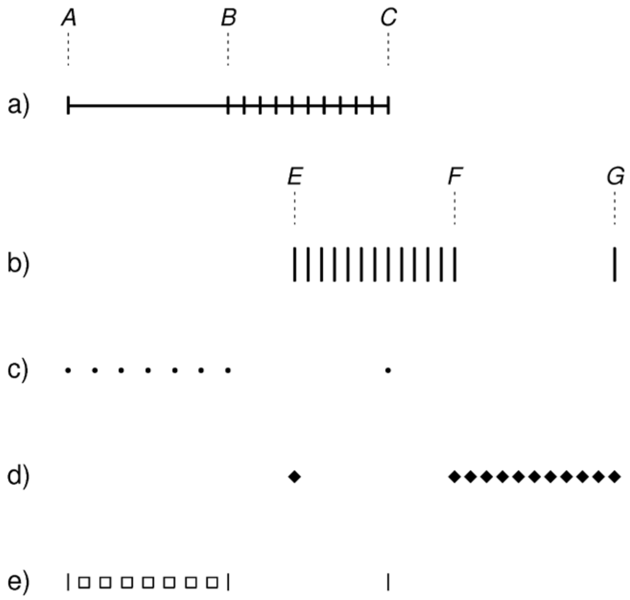

Fig. 1. Oppel–Kundt phenomenon. (a) The line segment marked by strokes *B*, *C* is perceived as longer than that marked by strokes *A*, *B*. (b) The distance between markers *E*, *F* is perceived as greater than that between *E*, *F*. Physically, the distances are exactly equal, $AB = BC$, $EF = FG$. The same effect is observed in arrays of simple dots (c) or spatially extended elements (d). (e) The apparent distance between the vertical strokes is affected by interspersed elements of different appearance.

to subdivide the path, and with varying numerosity of dividers the total amount of the optical matter[1] filling up the given space varies, too. The same argument applies to variations of length of the dividers; therefore, the numerosity effect and filling-up effect are not easy to disentangle on the basis of available data. In addition, the fact that the dependence of the illusory effect on numerosity and extent of the dividers obeys the same functional form (Wackermann and Kastner 2010) suggests a tempting hypothesis: may the observed effect be simply a function of the quantity of the optical matter contained in the area between the delimiters? Alternatively, if the illusory expansion can be varied while the amount of the filing-up optical matter is constant, then the effect must be due to other geometric properties of the stimulus figure. Since none of the reports known to us addressed this question directly, this was the aim of the reported study.

[1] The term "optical matter" is used here for "what the figure is made of", that is, the visual quality differentiating the stimulus figure from its background. It is not to be identified with the "matter" of the physical stimulus.

METHODS

Subjects

Twelve subjects, six women and six men (age range 21–28 years, mean age 24.2 years) of reportedly normal vision and not using any corrective vision aids, participated in the study. The participants were not familiar with the experimental paradigm; they signed an informed consent before and received a moderate financial compensation after the experimental session.

Apparatus

The same experimental setup was used as in our previous studies (Wackermann and Kastner 2009, 2010). Stimuli were presented on a 19" TFT monitor placed at a distance of 130 cm from the subjects' eyes. The subjects were watching the display binocularly, using a chin/forehead support, and operating with their dominant hand a pointing device connected to an iBook G4 computer controlling the experiment. An X11 based application *okfdisp* was used to generate the stimuli and to record the subjects' responses.

Tasks

Two tasks, bisection and distance matching, were applied within a single experimental session. In the bisection task, the subject had to place a movable element V to divide the spatial distance between two fixed markers, S_0 and S_1, into two equal halves, $S_0V = VS_1$ (Fig. 2a). In the distance matching task, the subject had to to place the movable element V to reproduce the distance between the fixed markers, i.e., $VS_0 = S_0S_1$ (Fig. 2b). The element V could be quickly dragged and dropped at the destination position, or finely moved using a wheel control on the pointing device. The subjects' response was confirmed and the current trial finished by simultaneously pressing the left and right buttons on the pointing device.

In the bisection task the space between the markers S_0 and S_1 was empty. In the distance matching task, the space between S_0 and S_1 was either empty (control condition) or filled with a number of discrete visual elements[2] as described in the following subsection.

[2] In our previous communications (Wackermann and Kastner 2009, 2010) we referred to these as "expletive elements", derived from Latin *explēre* = to fill. Here we refrain from using this term because of idiosyncratic connotations of the word "expletive" in contemporary English.

For every stimulus type, four variants of the task were used, in which the movable element V was placed on the left (L) or on the right (R) side at an initial position near to (N) or far from (F) the spatial interval S_0S_1. Each of these four variants (LN, LF, RN, RF) was applied four times, in a pseudo-random order, so that 4 × 4 = 16 trials were run with every stimulus type.

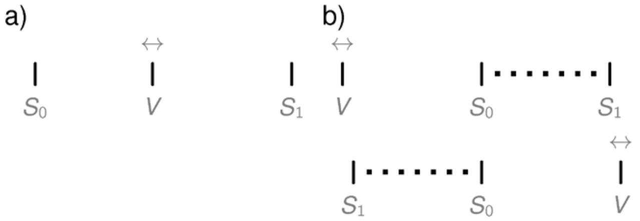

Fig. 2. Experimental tasks. (a) Bisection task. (b) Distance matching task (stimulus type M(4×4) used for the purpose of illustration).

Stimuli

The markers of spatial extents and the subdividing elements were drawn with neutral black on a bright white background (luminosity ratio ≈1:100). Markers S_0, S_1, V were vertical line segments of one picture element (p.e.) in width and of 16 p.e. in height (corresponding to visual angle 0.266°). The distance S_0S_1 was constantly 384 p.e. (visual angle 6.4°) for the bisection task, and 192 p.e. (visual angle 3.2°) for the distance matching task. Two series of stimuli (Fig. 3) were prepared for the distance matching task. In the "line splitting" series (S), the fillers were equispaced horizontal line segments of one p.e. width and a variable length, while the total sum of lengths was kept constant, 96 p.e. In the "filler morphing" series (M), the fillers were seven equispaced small rectangles of a variable height/width ratio h_y/h_x, but of a constant area $h_x \times h_y$ = 16 sq. p.e. Therefore, in the S-series the number of fillers varied, in the M-series the number of fillers was fixed. The total area covered by the filling elements was constant within both series. The relative coverage of the rectangular area marked by S_0 and S_1 was 3.1% for the S-series and 3.6% for the M-series, respectively.

Procedures

To introduce the subject to the experimental tasks, the session started with three "warm up" trials, the results of which were discarded. The proper experimental session consisted of 8 bisection trials followed by 176 distance matching trials. In the first 16 trials of the distance matching task, the space between S_0 and S_1 was left empty (control condition).[3] The subsequent series of 160 trials of the distance matching task consisted of two blocks of 5 × 16 = 80 trials each, using the five S and M types of the stimulus figure in a counter-balanced design. Within each block, variants of stimuli belonging to the given form were presented in a pseudo-random order. A complete session thus comprised 8 + 16 + 2 × 80 = 184 trials. As in our earlier studies, the participants had freedom of choice as to the positioning technique, i.e. drag-and-drop or wheel control; most subjects used a combination of both methods. No time limit was imposed. The typical total session duration was from 52 to 70 minutes (interquartile range). A total of 2 208 responses was collected, 96 for the bisection task and 2 112 for the distance matching task. Only the distance matching data, relevant for the subject matter of the study, are reported here.

Data reduction and analysis

Elimination of deviating responses

Data were examined for "outliers", i.e. for responses largely deviating from the subject's central response tendency, using the same "data peeling" algorithm as in previous studies (Wackermann and Kastner 2010, Appendix A). On an individual basis, the procedure was applied separately to data subsets obtained with variants

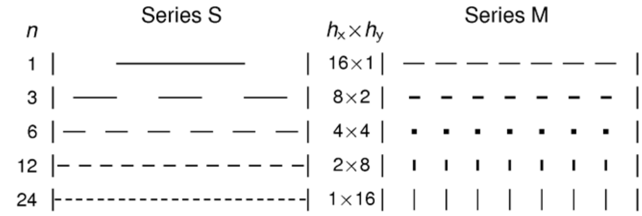

Fig. 3. Visual stimuli used in the experiments. Series S was obtained by successive splitting of a horizontal line of 96 p.e. length into n segments. Series M: array of n=7 rectangular elements of variable dimensions and constant area 16 sq. p.e.

[3] This served a smooth transition from the bisection task (moving element V between the markers S_0, S_1) to the distance matching task (moving element V on the left or right hand side of the interval marked by S_0, S_1). Note that the effect magnitude was evaluated relatively to the geometrically correct response, not to the control condition. The control condition data (shown in Fig. 4 as n=0) were used to verify that the subjects understood the instruction properly and practiced the manipulations adequately.

R or L for all different stimulus types. With the exclusion criterion c=4.5, the procedure detected 20 outliers (≈0.9% of all data). The outliers were replaced by the arithmetic means of the remaining data points within the respective data subset, to preserve a balanced experimental design.

Effect measure and statistics

The effect measure was a relative deviation from the geometrically correct response,

$$r = \frac{v - s}{s} \,,$$

where $s := S_0S_1$, and $v := VS_0$. Arithmetic means of these r values across 16 trials were calculated for each subject and each of the 11 stimulus types (one control condition + five variants within each of the stimulus series, S and M); these average effects $\bar{r}$ entered subsequent statistical analyses. The symbol $\bar{\bar{r}}$ denotes grand means evaluated across all 12 subjects. Global tests of deviation of the effect from zero, and of its dependence upon the varied stimulus parameter, rely upon one-way analyses of variance. *Post hoc* tests of the effect deviating from zero for singular values of stimulus parameter are based on one-sample t-tests.

RESULTS

The group average effects are shown in Figure 4. Expectedly, no effect was seen in the control condition (n=0), where the space between the markers was empty ($\bar{\bar{r}}$ =−0.003, $t_{df=11}$=−0.91, ns).

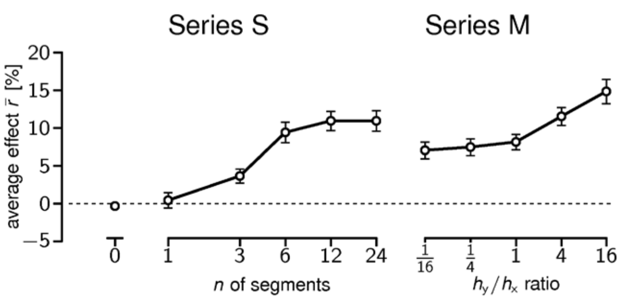

Fig. 4. Average effects displayed as functions of the respective control parameter (log scale), number of line segments n (series S) or ratio of filler sides h_y/h_x (series M). n=0 shows results for the control task with the space between S_0, S_1 being empty. Error bars indicate probable errors of the grand means.

In the S-series, the effect co-varied significantly with the number of fillers n ($F_{df=4,55}$=7.262, P<0.001). No significant difference from zero was found for n=1 (a single horizontal line segment; $\bar{\bar{r}}$ =0.004, $t_{df=11}$=0.30, ns). A positive effect (illusory expansion) was observed for n>1 segments, increasing rapidly to a saturation plateau at n=12 and 24, where $\bar{\bar{r}}$ =0.109 and 0.110, respectively ($t_{df=11}$=5.69, 5.61, both P<0.001).

In the M-series, the effect co-varied significantly with the form of the rectangular fillers, represented by the ratio h_y/h_x ($F_{df=4,55}$=3.462, P<0.02). The expansion effect was positive for all five forms used ($t_{df=11}$ in the range from 4.45 to 6.57, all P<0.001). The effect magnitude varied only slightly from h_y/h_x =1/16 (horizontal line segments) to h_y/h_x = 1 (square elements), $\bar{\bar{r}}$ =0.071, 0.074, 0.081. For h_y/h_x = 4 and 16 (vertical line segments) we observed a steep increase up to a doubled effect magnitude: $\bar{\bar{r}}$ =0.115 and 0.148, respectively. The latter value is in a good agreement with the maximal effect magnitude $\bar{\bar{r}}$ =0.151 obtained with a similar stimulus pattern in our previous study (Wackermann and Kastner 2010).

DISCUSSION

What is the bearing of the present results on our understanding of the OK phenomenon, and for the theory of GOIs in general? Firstly, we should point out that at present there is no plausible and generally accepted explanation of the OKI. The early theories proposed by Hering (1861) and Kundt (1863) were demonstrably deficient (Aubert 1865). The same is true for Wundt's (1898) attempt of explaining the OKI by eye movements and resulting muscular fatigue. Perhaps the most thorough experimental study of the OKI up to the present time was carried out by Spiegel (1937); yet, his theoretical account of the phenomenon in terms of "forces" acting in the perceptual organization of the visual field – in line with the Gestalt school tradition – was more of a speculative verbal exercise than a developed theory. Relatively recently some promising results in computational modeling of the OKI and other "illusions of extent" (e.g. Müller-Lyer) have been obtained (Bulatov et al. 1997, Bulatov and Bertulis 1999, 2005). It remains to be seen, still, how much of the evidently multi-factorial determination of the OK effect can be accounted for by those models.

Our results establish links between the OKI and other "illusions of extent", which may occur in one dimension (i.e., apparent length) or in two dimensions (i.e., apparent area) – as, for example, in Helmholtz' squares (1867) or Botti's rectangles (1906) – and are observed also in more complex visual patterns than regular arrays of uniform elements.[4] For example, Giora and Gori (2010) found the illusory expansion of rectangular areas filled with regular or random checkerboard patterns to be a non-monotonic function of the number of filling elements, similarly to our findings for the OK phenomenon (Wackermann and Kastner 2010). It seems that in the realm of GOIs non-monotonic effects are rather a rule than an exception, or even a characteristic signature of these phenomena.

As for the determining factors, we can say with certainty that the OKI is not merely an effect of "interruption" or "subdivision" of a given extent: there are numerous findings of its being dependent on other factors than only on numerosity of dividers. Therefore, the OK phenomenon is better accommodated in the class of "filled space expansion" phenomena (Lotze 1852, Lewis 1912, Wackermann and Kastner 2009, Giora and Gori 2010). However, the present results show that it cannot be reduced to a plain "filled vs. empty" effect. If the effect were dependent solely on the relative coverage of the delimited area with the optical matter, then we should observe a positive effect which, however, would be invariant with respect to different patternings and forms of the filling elements. This is evidently not the case. Instead, in the "line splitting" series S we observe a monotonic increase of the effect with an increasing number of horizontal line segments, saturating at 11% for the finest subdivision. In the "filler morphing" series M, the effect is almost invariant for horizontally extended or square-like elements, but it shows a steep increase for $h_y > h_x$ and reaches 15% with vertically extended fillers, consistently with our earlier studies. These results provide sufficient evidence against the simple "filling up" hypothesis stated in the Introduction.

Considering the non-linear, non-monotonic functional dependences on determining factors known up to now, it is unlikely that the effect results from additive contributions of different stimulus properties; more probably we are facing "emergent interactions" between them (Sarris 2010), resulting in differential effects of various stimulus patternings. Previous studies (Wackermann and Kastner 2009, 2010) as well as results obtained in the "filler morphing" series in the present study suggest a spatial anisotropy of the expansion effect, which acts predominantly in the direction orthogonal to the edges of the filling elements, and is thus more expressed for vertically oriented line strokes or rectangles.[5] This finding may make us think of a possible involvement of direction-specific edge detectors in the visual system. However, it would be premature to hypothesize about underlying neural mechanisms on the basis of present data. We should aim first at a purely phenomenological theory (Wackermann 2010), before more quantitative data are obtained and an adequate model of the phenomenon is constructed. Such a model would be an important step toward a mathematical theory of the content-dependent metric of the visual field[6]. Only then causal explanations may be attempted.

CONCLUSIONS

The reported study examined the effects of different filling patterns in the Oppel–Kundt phenomenon, where the relative coverage of the marked part of the visual field with the optical matter was constant within each of the two series of stimuli.

(1) Illusory expansion was observed when filling the space with $n>1$ horizontal linear segments. The effect reached a saturation of ≈11% for the two finest filling patterns ($n=12$ and 24, corresponding to segment lengths of 8 and 4 minutes of arc, respectively).

(2) Illusory expansion was observed when filling the space with $n=7$ rectangular filling elements of variable form. The effect was almost invariant for horizontally elongated elements, and increased by a factor of two up to ≈15% for vertically elongated (i.e., orthogonal to the action axis of the effect) elements of height 16 minutes of arc.

(3) The Oppel–Kundt phenomenon is not exclusively an effect of a single factor, either of the subdivision of a given extent, or of its "filling up" with optical matter. The magnitude of the illusory effect depends signifi-

[4] In fact, Oppel's (1861) original observation was made in two-dimensional drawings of squares on sheets of lined paper. One-dimensional illustrations of the phenomenon, similar to those shown in Fig. 1, are due to Hering, Helmholtz and later authors. Experimental studies of the OKI continued this tradition of reducing the phenomenon to a single dimension, which precluded for decades the connection between the OKI and other "filled space" effects.

[5] We assume, on a preliminary basis, that it is mainly the angle between the contours of the filling elements and the axis of the stimulus figure which matters: an assumption which should be experimentally proven.

[6] Several authors observed recently, and independently from each other, an analogy between a general theory of visual space, and that of physical space, namely the problem of determination of the space metric by the material content of the space: Wagner (2006), Westheimer (2008), Wackermann and Kastner (2009).

cantly on the patterning of the filling matter, or on shaping of the filling elements.

(4) The reported data, together with earlier findings, suggest a spatial anisotropy of the expansion effect, namely, a repulsive action in the direction orthogonal to the edges of the filling elements. This fact should be accounted for by future models of the OK phenomenon.

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