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Determinants of filled/empty optical illusion: Influence of luminance contrast and polarity

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Subjective estimates of lengths or areas in the visual field depend on the visual contents of the estimated space (filled/empty or Oppel–Kundt illusion). We studied the dependence of this phenomenon on the presentation mode (white on black vs. black on white background), and on the figure/ground contrast. We found, as expected, overestimation of the filled part of the figure for both contrast polarities. The expansion effect was found to be an increasing function of the absolute luminance contrast, and was consistently higher for the negative (luminant figures on a dark background) than for the positive polarity. The contrast factor contributes from one-fifth to one-third of the total effect. Possible interpretations in terms of known sensory phenomena (irradiation, lateral interactions) or higher, integrative functions are discussed.

Key words: figure/ground contrast, filled space expansion, geometric–optical illusions, irradiation, lateral interactions, luminance, Oppel–Kundt illusion

INTRODUCTION

A path in the visual field that is subdivided by a number of equally spaced markers is usually perceived as longer than an undivided path of the same length (Fig. 1a). This phenomenon, known as Oppel–Kundt illusion (OKI) (Oppel 1861, Kundt, 1863), can be understood as a special case of the "filled space expansion" effect: an area in the visual field, comprising a number of (regularly or randomly) displaced visual elements, is perceived as larger (in one or more directions) than an empty area of the same extent. Other examples of the filled space expansion are provided by Helmholtz' (1867) rastered squares, Botti's (1906) figures, or areas filled with complex textures (Giora and Gori 2010). The direction and magnitude of the expansion effect depend on many factors, such as numerosity, spatial density, form and orientation of the interspersed elements. The effect magnitude appears to be a non-linear, and even non-monotonic function of geometric properties of the stimulus (Spiegel 1937, Bulatov et al. 1997, Giora and Gori 2010, Wackermann and Kastner 2010, Wackermann 2012b).

The OKI can be observed in black figures drawn on a white background, as shown in the most of reference works (e.g. Coren and Girgus 1978, Robinson 1998), or in figures of inverted luminance polarity (e.g. Wundt 1898: Fig. 10).[1] Most of experimental studies of the OKI used only one presentation mode – either positive or negative polarity. Compared to geometric determinants of the illusory expansion effect, studies of its dependence on optical properties of the stimulus are rather rare. The only study known to us, in which the two presentation modes were compared and stimulus contrast varied systematically, was that by Spiegel (1937), while other authors examined effects of varied luminance contrast on the OKI magnitude (Dworkin and Bross 1998), or used elements of varied contrast superimposed on standard forms of geometric–optical illusions (GOI) (Bulatov and Bertulis 2005).

Our previous studies revealed an important role of contour elements in the illusory expansion effect, be it their length (Wackermann and Kastner 2009, 2010)

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[1] This observation applies not only to the OKI but also to many classic "geometric–optical illusions"; cf. the original presentation of the Hering (1861: Fig. 25) illusion and its inverted reproduction in Wundt (1898: Fig. 34).

or their orientation (Wackermann 2012a). These elements are essentially defined by intensity gradients in the visual field, i.e., by loci of the maximum luminance contrast. Therefore, influence of these properties of the stimulus on the OKI effect is to be expected, and is a potentially important issue for the interpretation of this phenomenon. Facing a relative scarcity of reports on the effects of contrast and polarity on the OKI and, on the other hand, a great diversity of contexts and methods (reproduction, forced-choice comparison, magnitude estimation) used by their authors, we decided to explore these effects systematically.

METHODS

Subjects

Twelve subjects, seven women and five men in the age range from 18.8 to 29.7 years (mean = 23.9 years), participated in the study, each subject in one session. All participants were reportedly of good health and had normal vision. They were explained the aim of the study and the experimental procedure, and signed a written consent before the session; after the session they received a moderate financial compensation.

Visual acuity of the observers was not measured; the selection criterion was their reporting normal vision, not using any vision aids, and confirming that they could see the visual elements of the stimulus figure sharply and distinctly.

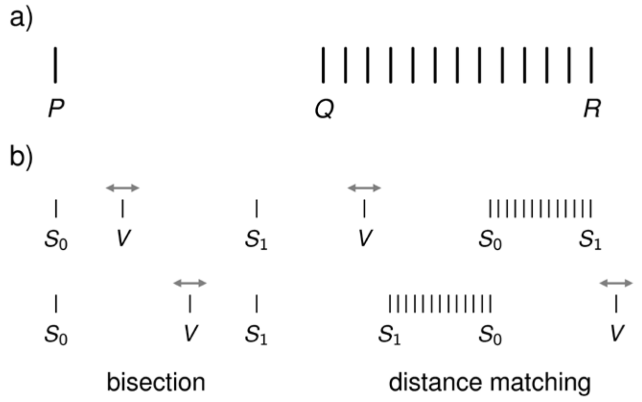

Fig. 1. (a) Oppel–Kundt phenomenon. The distance between strokes Q and R appears larger than the distance between strokes P and Q, although geometrically the two distances are equal, $PQ = QR$. (b) Tasks used in the reported study. In the bisection task (left), a movable element V (marked by a left/right arrow) has to be placed so that $S_0V = VS_1$. In the distance matching task (right), the element V has to be placed so that $VS_0 = S_0S_1$.

Apparatus

Visual stimuli were generated by the *okfdisp* program running on an iBook G4 (Apple Inc.) computer and displayed on a 27” LCD monitor (NEC PA241W) that was operated at its native resolution 2560 × 1440 picture elements. Observed from a constant distance of 106 cm, one picture element (p.e.) on the display subtended 0.875 minute of arc. A pointing device (“mouse”), manipulated by the subject, was connected to the control computer.

Tasks

Subjects were given two types of tasks (Fig. 1b). A visual element, V, was displayed along with the stimulus figure, and could be moved with the pointing device. In the bisection task, the subject had to position V in the center between the two delimiters, S_0 and S_1, so that $S_0V = VS_1$. In the distance matching task, the subject had to position V so that the distance between V and the proximal delimiter S_0 was equal to the distance between the delimiters S_0S_1. The main purpose of the bisection task was training the subject in perception of equality of spatial extents, and so preparing her/him for the distance matching task; the latter task was used to evaluate the Oppel–Kundt effect and its dependence on stimulus variations.

Stimuli

In the first part (A) of the experiment, the filled space expansion effect was examined as a function of the number n of filling elements, using high-contrast stimuli and two alternating contrast polarities, positive (black on white) and negative (white on black). In the second part (B) of the experiment, dependence of the filled space expansion effect on the visual contrast was studied, using stimuli of graded, positive or negative contrasts with a constant number of the filling elements. The variety of used stimuli is shown in Figure 2.[2]

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[2] Fig. 2 provides only a qualitative impression of the visual appearance of the stimuli; an exact reproduction of contrasts in print cannot be guaranteed.

Geometry

Stimuli were horizontally arranged equispaced arrays of short vertical lines (markers) of one picture element (p.e.) width and 17 p.e. height (≈0.25°). The distance between the delimiters S_0 and S_1 was constantly 384 p.e. (5.6°) in the bisection task, and 192 p.e. (2.8°) in the distance matching task. In the bisection task as well as in the control condition of the distance matching task, the space between the delimiters was empty; otherwise the space was subdivided by n filling elements of the same height as the delimiters into n+1 segments of equal length. In Part A, n=0 (control condition), 5, 11, and 23 fillers were used. This choice was based on results of a previous study (Wackermann and Kastner 2010), where the maximum of the illusory effect was found for $11 \leq n \leq 13$ fillers, while lower effects were observed for smaller or greater n. In Part B, n=11 fillers were used, for which maximal illusory effect was expected.

Luminance contrast

The figure/ground contrast was defined on the decilog scale (dL) by

$$k = -10\log_{10}\frac{L_\mathrm{F}}{L_\mathrm{B}} \tag{1}$$

where L_F and L_B denote the foreground and the background luminance, respectively.[3] The minus sign in (1) is chosen to have negative k values for figures of "negative" appearance (e.g. white on black); it is only a matter of convenience. In Part A, high-contrast stimuli (k =±20 dL) were used, drawn with dark gray (L_F=2 cd/m^2) on a bright white background (L_B=200 cd/m^2) for the positive contrast, or with bright white on a dark gray background ($L_\mathrm{F} \leftrightarrow L_\mathrm{B}$) for the negative contrast. In Part B, stimuli of relatively low, graded contrast were used: the background was neutral gray (L_B=20 cd/m^2), and the foreground luminance was varied at 2 × 3 levels: L_F=10, 5, and 2.5 cd/m^2 for the positive, and L_F=40, 80 and 160 cd/m^2 for the negative polarity. These variations yield contrast values ±3, ±6, and ±9 dL, respectively.

Procedures and design

Subjects were watching the display binocularly from a constant distance of 106 cm, secured by a chin/forehead support. The monitor was covered by a black cardboard mask with a rectangular opening of 26.5 × 9 cm, making only the stimulus figure visible and concealing the program's control elements from the subject's sight. Subjects could use the "drag-and-drop" technique to manipulate the movable element V, or use a wheel control on the pointing device for its fine positioning. No time limit was imposed.

Part A of the experimental session consisted of two sequences of trials ("runs"), each run comprising 72 trials. Each run began with eight bisection trials; these were followed by 16 distance matching trials with n=0, i.e., the space between S_0 and S_1 being empty (control condition). The run continued with 48 distance matching trials, using different numbers of fillers n_1, n_2, n_3, permuted across subjects, in consecutive blocks of 16 trials. Positive and negative contrasts were alternated between the two runs in a counter-balanced order (positive–negative for six subjects, negative–positive for another six subjects). Part B consisted of six blocks by 16 trials, in which the number of fillers was constantly n=11, and the stimulus contrast was varied in the ascending or descending order; the pre-

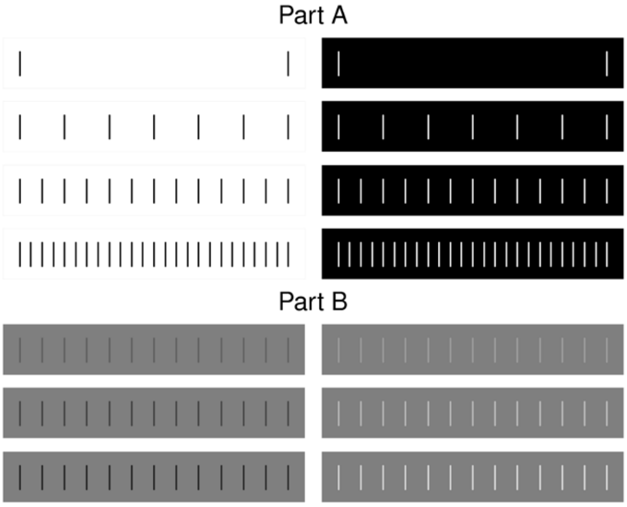

Fig. 2. Stimuli used in the reported study. In Part A, the number of fillers was varied (n=0, 5, 11, 23), using the highest contrast at two polarities (k=±20 dL). In Part B, the contrast was varied gradually (k=±3, ±6, ±9 dL), using a constant number of fillers n=11. Note: Only reference parts S_0S_1 of two-parts figures (cf. Fig. 1) are shown; the movable element V was of the same appearance.

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[3] Foreground luminance L_F was measured from a screen patch filled uniformly with the gray-shade which was used for drawing the stimulus figure. These values are thus merely nominal; "real" contrasts may have been slightly different due to the light scattering between the LCD display elements.

sentation order was counter-balanced across subjects. In sum, each subject contributed a total of 240 trials to the database, 144 trials in part A, and 96 trials in part B.

Data reduction and analysis

Elimination of deviating responses

Responses largely deviating from the subject's central tendency ("outliers") were detected, using a "data peeling" algorithm (Wackermann and Kastner 2010, Appendix A) with the exclusion criterion c=3.5 applied separately to distance matching data subsets for each subject and experimental condition. Altogether 16 outliers were detected (≈0.6% of all data). The outliers were replaced by arithmetic means of the remaining data points within the respective data subset, to preserve a balanced experimental design.

Effect measure and statistics

A relative deviation of the distance $v := VS_0$ marked by the subject from the correct distance $s := S_0S_1$ was taken as the effect measure:

$$r = \frac{v-s}{s} \tag{2}$$

Arithmetic means were calculated across subsets of 16 trials for each subject and experimental condition and used in the subsequent statistical analyses. These are in the following denoted $\overline{r}_\mathrm{A}(n,k)$ or $\overline{r}_\mathrm{B}(n,k)$; but we drop unnecessary indices wherever they can be inferred from the context. The symbol $\overline{\overline{r}}$ denotes grand means, i.e., group averages of $\overline{r}$ calculated across all subjects. To separate the common from the differential component of the effect, averages of and differences between effects $\overline{r}$ for opposite contrasts k were calculated,

$$\begin{aligned} \tilde{r}(n,k) &= \frac{1}{2}\big(\overline{r}(n,+k)+\overline{r}(n,-k)\big) \\ \Delta r(n,\pm k) &= \overline{r}(n,+k)-\overline{r}(n,-k) \end{aligned} \tag{3}$$

Grand means of these transformed quantities are denoted $\overline{\tilde{r}}$ and $\overline{\Delta r}$, respectively.

Tests of deviations of grand means $\overline{\overline{r}}$, or transformed measures $\overline{\tilde{r}}$, $\overline{\Delta r}$, from zero were based on one-sample t tests. Two-tailed P values are reported for differential effects; however, t values and the corresponding P values are not reported for the main effects, since these effects were trivially highly significant (all $t_{\mathrm{df}=11}>5$ or higher).

To characterize individual susceptibility to the illusory effect, average responses across experimental

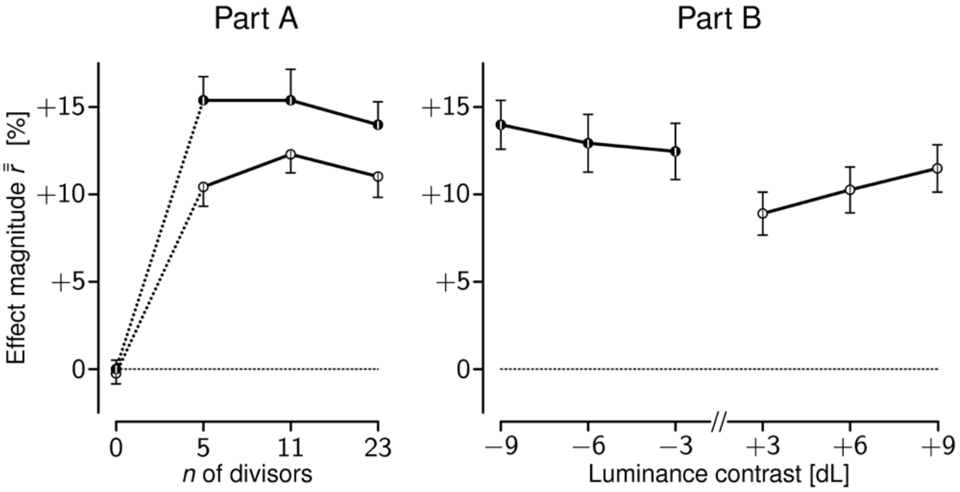

Fig. 3. (A) Average effects $\overline{\overline{r}}$ plotted as functions of the number of fillers n, shown for positive and negative visual polarity of the stimulus figure. (B) Average effects $\overline{\overline{r}}$ plotted as functions of positive and negative contrasts varied at three levels. Contrast polarity is distinguished by graphic symbols: white-filled circles with black strokes for the positive and black-filled circles with white strokes for the negative contrast. Shown are group-based (n=12) grand means ±1 SEM.

conditions were calculated separately for Part A and Part B, for each subject:

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\begin{aligned}
a_{\mathrm{A}} &= \frac{1}{6}\sum_{n}\sum_{k}\bar{r}_{\mathrm{A}}(n,k) \\
a_{\mathrm{B}} &= \frac{1}{6}\sum_{k}\bar{r}_{\mathrm{B}}(n,k)
\end{aligned}
\qquad (4)
$$

In the formula for a_{A}, the sums are taken over all conditions $n = 5, 11, 23$ and contrasts $k=\pm 20$. In the formula for a_{B}, the sum is taken over all contrasts $k=\pm 3$, ± 6, and ± 9 dL, with constant $n=11$.

RESULTS

In Part A, the group mean $\bar{\bar{r}}$ did not differ significantly from zero (i.e., no effect) for $n=0$ (control condition), whereas positive group mean effects were obtained for $n>0$. With increasing $n=5$, 11, 23, the group mean effects were $\bar{\bar{r}}=0.104$, 0.123, 0.110, respectively, for the positive contrast polarity (black lines on white background), and $\bar{\bar{r}}=0.154$, 0.154, 0.140 for the negative contrast polarity (white on black background). The space expansion effect was thus consistently greater for the negative than for the positive contrast; in addition, we observe a shift of the maximum effect toward lower n in the negative contrast condition. In Part B, group mean effects were all positive, ranging from $\bar{\bar{r}}=0.089$ to 0.115 for the positive contrast levels, and from $\bar{\bar{r}}=0.124$ to 0.140 for the negative contrast levels. Again, the space expansion effects were consistently greater for negative contrast levels, and showed a slightly increasing trend with increasing $|k|$. The results are graphically summarized in Figure 3.

A more comprehensive picture is obtained by transforming the individual mean responses $\bar{r}$ into averages $\tilde{r}$ and differences Δr (Eq. 3). The $\tilde{r}(n,k)$ values thus represent the common (contrast-symmetric) component of the effect as a function of n (Part A) or $|k|$ (Part B), respectively, while the $\Delta r(n,k)$ values represent the differential (contrast-antisymmetric) component of the effect. Group statistics of the transformed measures are summarized in Figure 4.

In Part A, the common component of the expansion effect had a maximum $\tilde{r}=0.138$ for $n=11$, and was slightly lower for lower or higher n (0.129 for $n=5$, 0.125 for $n=23$). The differential effect was maximally expressed at $n=5$, where $\overline{\Delta r}=-0.05$ ($t_{\mathrm{df}=11}=2.92$, $P<0.02$), and approximately constant (-0.03) for higher numbers of fillers (non-significant for $n=11$, significant for $n=23$: $t_{\mathrm{df}=11}=2.74$, $P<0.02$). Ratio $|\Delta r|/\tilde{r}$, estimating a relative contribution of the differential to the common effect, was 0.38 (maximum) for $n=5$, and distinctly lower, 0.22 and 0.24, for higher n.

In Part B, the common component of the expansion effect was a linearly increasing function of $|k|$, ranging from $\tilde{r}=0.107$ to 0.127, while the differential effect ranged from $\Delta r=-0.037$ ($|k|=3$ dL) to -0.025 ($|k| = 9$ dL). All differential effects were significantly different from zero ($t_{\mathrm{df}=11}$ from 2.98 to 3.44, $P<0.02$), whereas the variations across contrast levels were non-significant. Ratio $|\Delta r|/\tilde{r}$ attained a maximum 0.33 for the lowest contrast, $|k| = 3$ dL, and was distinctly lower, 0.23 and 0.20, for higher contrasts.

Inspection of individual data revealed large inter-individual variability of mean responses. This aspect of the data is roughly assessed by the individual averages across conditions for parts A and B (Eq. 4). These average effects ranged from 0.028 to 0.213 (median 0.131) in part A, and from 0.005 to 0.221 (median 0.108) in part B.[4] A very high Pearson's correlation between a_{A} and a_{B}, +0.928 ($df=10$, $P<0.001$), indicates that the response variability in the two parts of the experiment was due to individual differences in susceptibility towards illusory perception, and not merely random fluctuations of individual responses.

DISCUSSION

Our results show that the filled space expansion effect is significantly influenced by the figure–ground luminance contrast of the stimulus. The relative contribution of the contrast factor is up to ≈40% (but usually less) of the common effect. In both parts A and B of the experiment, stimuli of negative contrast produced greater effects – that is, overestimation of the filled part of the stimulus figure – than stimuli of positive contrast.

These findings are generally in agreement with those of Spiegel (1937), who used stimuli of negative contrast (arrays of luminant line segments displayed on a dark background) as standard stimuli, and observed a significant decrease of the effect magni-

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[4] In fact, the minimal values of a_{A} and a_{B} were obtained from the same subject who should be classified as an almost perfect 'non-reactor' to the OKI. However, we had no reason to exclude this subject from the statistics.

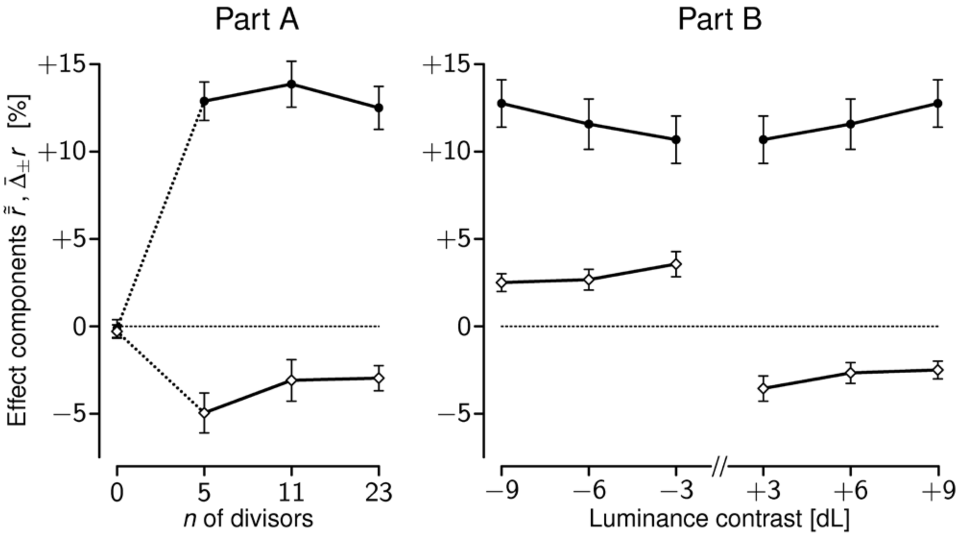

Fig. 4. Common components $\bar{\tilde{r}}$ (filled circles) and differential components $\overline{\Delta r}$ (open rhomboids) of observed effects plotted (A) as functions of the number of fillers *n*, and (B) as functions of varied contrast *k*. Shown are group-based (*n*=12) grand means of transformed data (see Eq. 3) ±1 SEM.

tude for stimuli of positive contrast. Unlike our data, however, Spiegel's data do not indicate any shift of the maximal effect toward lower number of fillers. Results from Part B of our experiment also seem to agree qualitatively with the report by Dworkin and Bross (1998), according to which greater illusory expansion was observed in stimuli of higher brightness contrasts.[5]

Data on contrast effects on the OKI are scarce, but more work has been done on other kinds of geometric–optical illusions, such as the Müller-Lyer illusion (Wickelgren 1965), the Orbison illusion (Davidoff 1973), the Delboeuf illusion (Weintraub et al. 1969, Surkys et al. 2006), the Ebbinghaus illusion (Jaeger and Pollack 1977), or for groups of diverse GOIs (Li and Guo 1995, Hamburger et al. 2007, Daneyko et al. 2011). These reports seem to reveal a common tendency to increasing illusory effects with increasing figure–ground luminance contrast. However, generalizations are still hardly possible, because of the multitude of phenomena involved (ranging from alterations of perceived extent to distortions of angles and forms), a great variety of presentation techniques (unrestricted view vs. tachistoscopic presentation) and measurement methods (magnitude estimate, compensation techniques), apparent complexity of interactions between phenomenal features, and last but not the least, different research motivations.[6] It is thus fair to say that the question at which level of the visual system the interaction between the geometric and optical properties of the stimulus occurs to give rise to a distorted percept, still remains an open question.

A possible candidate might be the brightness–size interaction, in earlier literature referred to as "irradiation" (Plateau 1842, Helmholtz 1867): a luminant figure displayed against a dark background appears larger than the same figure of reversed polarity (Van Erning et al. 1988). Since irradiation is not a simple phenomenon but rather a bundle of "perceptual phenomena produced by optical, neural, photochemical, and psychological mechanisms" (Haines 1970: p. 197), its explanatory potential is rather problematic. Irradiation was proposed as a common explanation for a group of GOIs (Lehmann 1904), but its role seems to be restricted to edge shifts and tilts underlying shape distortions, as for example in the "shifted checkerboard" (Münsterberg 1897, Pierce 1898) and its derivates (Fraser 1908, Gregory and Heard 1979, Kitaoka 1998,

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[5] Quantitative comparisons of results in terms of contrast values and effect magnitudes are impossible, firstly, because of extremely terse wording of the source, and secondly, for significant methodical differences.

[6] In the last three decades, the focus of interest significantly shifted from descriptive investigations of GOIs to their use as experimental tools for testing hypotheses about the visual system. This line of research, originating in influential papers by Hubel and coworkers (Livingstone and Hubel 1987, 1988), emphasized segregation of visual information to separate channels, whereas our problem is the opposite, namely, the re-integration of diverse dimensions of the stimulus in a unitary, and possibly altered, percept. Due to this shift, effects of luminance contrast seem to be of little interest per se, but are mostly reported for comparison with color-contrast conditions. Accumulated evidence from psychophysical experiments has corrected initial simplifications concerning the absence of GOIs in colored equiluminant stimuli; cf. Hamburger and coauthors (2007).

Roncato 2000). Importantly, no such contact interactions or angular distortions are involved in the OKI. Here, irradiation arguably could cause a widening (“blurring”) of the visual elements (delimiters and fillers) displayed with negative contrast (Bex and Edgar 1996), but widening the filling elements reportedly has no influence on the OKI effect magnitude (Spiegel 1937). Even if an illusory widening effect were added to the proper space expansion effect, its contribution should increase with the number of fillers; but our data show exactly the opposite, that is, a maximal differential effect with the minimal number of fillers (n=5). Also, if the differential effect were due to irradiation, we would expect maximal blurring at the highest negative contrast but no noticeable blur and thus no difference at low contrast. Our data, however, show a significant differential effect even at the lowest contrast levels ($k = \pm 3$ dL). Interestingly, Long and Murtagh (1984) studied the irradiation effect as a limiting case of the OKI for $n \rightarrow 0$ (i.e., uniformly white field) or $n \rightarrow \infty$ (i.e., uniformly black field) and found a qualitatively different behavior of the irradiation expansion from the genuine Oppel–Kundt phenomenon: irradiation effects were observable only in forced-choice comparisons between side-by-side stimuli, while the latter manifested itself robustly in pairwise comparisons as well as in direct estimates of extent of single stimuli. The differential effect thus cannot be explained by irradiation around the subdividing/filling elements. As for a brightness–extent interaction upon the spaces between the fillers, this would predict an opposite direction of the differential effect than observed in Part A of our experiment,[7] and is ruled out by the results of Part B, where the background luminance was kept equal for the stimuli of positive and negative contrast.

If irradiation as a cause can be safely excluded, another well-known mechanism acting in vision, namely “lateral inhibition,” deserves consideration. Békésy (1967:, pp. 228ff) attempted to explain a group of geometric illusions observable in the visual and tactile modality, among them also the OKI,[8] by lateral inhibition. In the same vein, Ganz (1964, 1966) proposed lateral inhibition as a common mechanism underlying figural after-effects and geometric–optical illusions. According to his theory, inhibitory interaction between neural excitation induced by neighboring visual contours shifts the maxima of their respective excitation distributions, which presumably correspond to their positions “as seen” in the visual field, and thus causes a “repelling effect” between the contours. As lateral interactions may involve both inhibitory and excitatory components (Westheimer 1967), this theory would account, in a more general framework, for both repelling and attracting interactions between visual contours. This is an attractive feature for a theory of the Oppel–Kundt phenomenon, since the interplay between the repulsive and attractive action might explain the non-monotonic dependence of the total expansion effect on the number of dividers, showing a decrease at high densities of subdividing elements (Spiegel 1937, Wackermann and Kastner 2010). However, such a generalized interactionist theory will have to overcome many difficulties, such as controversial findings in modified, more complex variants of well-known GOIs (e.g. Ebbinghaus illusion: Rose and Bressan 2002) as well as conflicting assumptions on the nature of inter-contour interactions (Ganz 1964, Pollack 1964).

Finally, we note in passing that our results provide an argument against simplistic cognitivist interpretations, such as the Tausch–Gregory “perspectival theory”. Tausch (1954) sought to explain the OKI in terms of perspectival depth cues: the subdivided part of the OKI figure was supposed to be as if at a larger egocentric distance from the observer than the unfilled part, and its horizontal extension accordingly overestimated.[9] However, lower contrast is normally associated with larger watching distances (“aerial perspective”: O’Shea et al. 1994), and so this theory would predict increasing expansion effect with decreasing contrast, i.e., exactly the opposite of our findings.

If, as it seems, interpretations of the differential effects of luminance polarity and contrast in terms of known perceptual mechanisms fail, then these effects must be taken as raw facts to integrate into a theory of the Oppel–Kundt phenomenon. One way to such a theory may be a stage-by-stage model of visual signal processing (Bulatov et al. 1997, Bulatov and Bertulis 2005, Chao et al. 2003, Fermüller and Malm 2004)

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[7] The fact that the expansion effect diminishes for OKI figures drawn on bright background, compared to stimuli of negative contrast and the same geometry, motivated Spiegel’s (1937) speculative theory of three forces interacting between the figure elements.

[8] Referring erroneously to the Oppel–Kundt illusion as “Helmholtz illusion” – cf. Békésy (1967), Fig. 183ab, p. 233.

[9] Tausch has to be mentioned as an unjustly forgotten precursor of Gregory’s (1963) widely popularized “constancy scaling” theory. The confabulatory observation of the subdivided part being seemingly “farther away” from the observer goes back to Wundt (1898: p. 82); cf. also Thiéry (1896: p. 125).

involving the luminance gradients at some processing level. An alternative approach would be a mathematical model of long-range repulsive interactions in the visual field, involving the distances between visual elements and relative orientations of their edges (Wackermann 2012a) as well as luminance differences at the edges (present work) as its basic constituents. Both modeling strategies are worth further exploring.

CONCLUSIONS

The reported study examined the effects of the presentation mode, i.e. positive (black-on-white) vs. negative (white-on-black) contrast, and of graded positive vs. negative contrasts for stimulus figures drawn on a neutral grey background, on illusory filled space expansion.

(1) The contrast polarity significantly influences the total effect, which is consistently higher for the negative than for the positive contrast. The differential effect of contrast polarity is highest for the lowest number of fillers *n*, which causes a shift of the locus of maximum effect towards lower *n*. The relative contribution of the contrast-related effect to the common effect is up to ≈40%.

(2) The figure–ground contrast (graded positive vs. negative contrast) plays a modulating role in the expansion effect. The differential effect slightly increases with increasing contrast, but the relative contribution of the differential effect is maximal at the lowest contrasts levels (about 33%).

(3) The observed effects of contrast polarity and level cannot be explained trivially in terms of the known brightness–extent interaction ("irradiation"). Lateral interactions, involving but not limited to "lateral inhibition", seem to be more promising candidates for an explanatory theory of the OKI.

(4) The locus and mechanisms of integration of optical and geometrical properties of the stimulus to produce the illusory effect are at present unknown. A model of these interactions remains a task for a theory of the OKI, and of the filled space expansion phenomenon in general.

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