Luminance-defined salience of homogeneous blob arrays

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For the quantitative analysis of luminance-defined salience, blob arrays on different backgrounds (5.5-68 cd/m^2) were adjusted until they appeared equally conspicuous. Matches of blobs at *same luminance polarities* (all dark or all bright) closely followed the constant-ratio rule; that is, blobs appeared equally salient when their luminance ratio to background was constant (Exp. 1-3). Gradual deviations from this rule reflected salience contributions from brightness perception and assimilation effects (Exp. 4 and 5). Bright targets, however, were special in that equal-salience matches could instead follow the constant-addition rule or intermediate settings when the blobs to be adjusted were the brightest items in the display. Matches of patterns with *different luminance polarities* (dark versus bright blobs) showed variable characteristics. On the same backgrounds, they closely followed the Weber contrast (equal increments and decrements) for small and medium luminance differences and saturated at larger blob contrast (Exp. 6). On different backgrounds, however, performance was better predicted by Stevens' brightness law, i.e. by constant differences of blobs and backgrounds on a power function (exponent $x<0.5$) of luminance (Exp. 7). The findings were partly confirmed in a final experiment in which pairs of patterns with predicted equal salience settings were reviewed for similar conspicuity (Exp. 8). Predictions were based on various algorithms and also made over a much larger luminance range (0.1-220 cd/m^2). While constant-ratio predictions were generally accepted for dark blobs, those for bright blobs were often rejected and better ratings instead obtained from constant differences in the power of luminance. Cross-polarity matches of dark and bright blobs were fairly tolerant at medium contrast and ratings little distinctive between algorithms. But when the luminance range was increased, best equal-salience ratings were again obtained for constant differences on Stevens' power function.

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INTRODUCTION

Numerous studies have stressed the important role of salience in visual tasks. Salience can attract focal attention and may thus help, or disturb target detection and recognition. It also affects visually guided behavior by modulating the selection of objects for gaze shifts, or for pointing and reaching (Beutter, Eckstein, & Stone, 2003; Borji, Sihite, & Itti, 2013; Itti & Koch, 2000; Koehler, Guo, Zhang, & Eckstein, 2014; Nothdurft, 2002, 2006a; Wood et al., 2011; van Zoest & Donk, 2005; Zehetleitner, Hegenloh, & Müller, 2011; Zehetleitner, Koch, Goschy, & Müller, 2013; for reviews see, e.g., Treue, 2003; Zhao & Koch, 2013).

While several parameters of target salience were identified over the last years, other aspects have remained unclear. It is well-known, and widely agreed on in the literature, that salience may derive from certain stimulus discontinuities such as differences in object size, luminance, orientation, motion (speed and direction), color, or depth (cf. Wolfe, 1998). But how all these differences exactly transform into salience, is not yet known. Apparently, discontinuities must be strong enough and locally detectable (Nothdurft, 1993; 1997; Sagi & Julesz, 1987), but it is not always clear how the strength of a feature gradient would affect perceived salience.

An important aspect of salience is its graded property; an object or target can be less or more salient than others (cf. Huang & Pashler, 2005; Nothdurft, 2006b; Poirier, Gosselin, & Arguin, 2008; Zehetleitner, Koch, Goschy, & Müller, 2013). This adds quantitative aspects to the pure detection of salience. The quantitative estimate of perceived salience is therefore an important goal both for a complete functional description of salience effects and for identifying the underlying mechanisms. This is particularly important, as modifications of target salience may have a strong effect upon target visibility in difficult tasks. While two targets of slightly unequal salience are usually both fast detected in a simple visual search task, their detection can be quite unequal when the visual system is engaged in a parallel, competitive task (Braun, 1994). These differences disappear when their salience is adjusted (Nothdurft, 2006b). Thus, understanding even the quantitative aspects of salience representations is a challenge for many areas of visual science including computational and machine vision.

Luminance-defined salience

One of the most prominent and frequent salience cues in vision is luminance; particularly bright (or dark) objects pop out from a scene and can be easily detected (Braun, 1994; Engel, 1974; Nagy & Sanchez, 1992; Nothdurft, 2000, 2002; Theeuwes, 1995; Turatto & Galfano, 2000). While a general salience effect from luminance has been questioned (Einhäuser & König, 2003; but see Borji, Sihite, & Itti, 2013; Parkhurst & Niebur, 2004; and the General Discussion below), there are several reports that the sudden onset or increment of a bright stimulus may attract attention and gaze (Irwin, Colcombe, Kramer, & Hahn, 2000; Mortier, Donk, & Theeuwes, 2003; Spehar & Owens, 2012; Theeuwes, 1994; Van der Stigchel, Mulckhuyse, & Theeuwes, 2009; Weichselbaum, Fuchs, & Ansorge, 2014). The common dependence of many salience effects on local differences, i.e. on feature *contrast* (Nothdurft, 2005), suggests that luminance-defined salience is related to luminance contrast, not luminance per se; but it is not certain to exactly which definition of contrast salience would correlate. Are there other influences, e.g. from the perceived brightness and lightness of a target?

The present study attempted to answer these questions by a systematic exploration of salience variations with luminance contrast. In this paper, I report investigations with regular arrays of similar items (squared "blobs"). Additional experiments on the salience of single targets among (different) distractors, on the linearity and nonlinearity of salience perception and on the possible influence of cognitive aspects will be presented in forthcoming papers.

GENERAL METHODS

The majority of tests reported here were *salience matches*. Subjects had to adjust the luminance of blobs in one pattern so that these appeared equally salient to blobs in a comparison pattern (Exp. 1-7). A variation of this task was the *confirmation task* (Exp. 8), in which subjects reviewed pre-set pairs of blob patterns and evaluated whether or not the blobs looked equally salient; subjects could not adjust blobs in these patterns. In both tasks, the two patterns to be compared were geometrically identical (not in Exp. 5) and differed only in background and blob luminance (Fig. 1). All adjustments were made on continuously visible stimulus displays within a luminance range of 5.5 cd/m^2 to 68 cd/m^2. In the confirmation task, additional tests were performed on a second monitor with a larger luminance range (0.1 cd/m^2 – 220 cd/m^2).

Stimuli

Patterns consisted of a regular array of 3 x 5 small squares (each 0.4 deg x 0.4 deg) at a raster width of 2.1 deg (cf. Fig. 1); in Experiments 4 and 5 also single blobs and other raster configurations were tested. In every stimulus presentation, two such patterns were shown side by side, one on the left and one on the right half of the monitor, at a center-to-center distance of 10.4 deg. To avoid contrast borders between the two backgrounds, the monitor was covered with a grey hard-paper mask with two vertical, rectangular holes (8.9 deg x 14.6 deg) centered over the two raster displays. All stimuli were computer-generated and displayed on a 17-inch monitor (60 frames/s) at a viewing distance of 75 cm. Part of the *confirmation task* was performed on an LCD monitor adjusted to the same stimulus geometry but a larger luminance range.

Luminance settings. Experiments were performed in a dim-lighted room (wall luminance 3–5 cd/m^2). Screen luminance (5.5–68 cd/m^2 and 0.1–220 cd/m^2, respectively) was varied under computer control to produce dark or bright blobs on bright or dark backgrounds. The corresponding luminance levels were measured offline and values repeatedly checked during the course of the study. Mask luminance was 2 cd/m^2 in the standard screen setting, and 6 cd/m^2 in tests with the large luminance range.

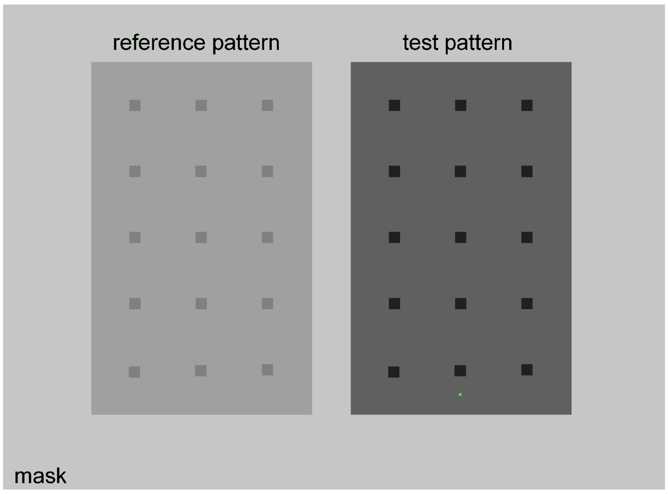

Figure 1. *Sketch of stimulus patterns.* Blobs in the two patterns are compared for salience. In the *matching task*, subjects adjusted the luminance of blobs in the "test pattern" until they matched the salience of blobs in the "reference pattern". In the *confirmation task,* subjects were asked to indicate whether or not blobs in the two patterns were about equally salient. Test and reference patterns were randomly located on either side of the screen at a center-to-center spacing of 10.4 deg. Most tests were performed on regular arrays of 3 x 5 blobs, each 0.4 deg x 0.4 deg, at a raster width of 2.1 deg. Monitor edges and edges between the two patterns were covered by a grey hard-paper mask. Text in the figure is only for illustration; in experiment, test patterns were identified by a tiny green dot underneath.

Tasks and Procedures

As already mentioned, salience estimates were made in two different tasks. In the *salience matching task*, subjects adjusted the luminance of blobs in one of two patterns ("test pattern") until their salience matched as closely as possible the salience of blobs in the second pattern ("reference pattern"). The *confirmation task* was a modification of this task; stimulus presentation was the same but subjects were asked to evaluate if the blobs in the two patterns were about equally salient.

For these tasks a large number of test series was generated, each with 3-12 individual test conditions (stimulus pairs). These series were sorted in "blocks" to group the various conditions to be tested. In a single run of a test series, every test condition was presented twice, with the positions of reference and test patterns exchanged, in random sequence. The test pattern was marked with a small green dot (0.1 deg diameter) underneath the blob array, to guide subjects which pattern they could adjust in the matching task. Test series were typically run two times and were repeated more often if there were large variations between repeated matches. Test series in the confirmation task included many more test conditions (typically 150<n<400) also presented in random sequence. All measurements were made in two-hour sessions, during which subjects could pause whenever they wanted.

Subjects made adjustments by pressing different keys on a computer keyboard ("+" or "-") to increase or decrease blob contrast, and pressed a third key ("a") when they decided that they had achieved the best possible match. There was no time pressure to finish adjustments, and subjects were free to look to and fro the reference and test patterns before hitting the "accept" key. Upon acceptance of an adjustment the screen was blanked for 1 s, before a new pair of stimulus patterns was presented. The procedure was identical in the confirmation task, except that subjects could not adjust blob luminance in one pattern but only accept or reject the presented stimulus pair.

Subjects were instructed to compare the *conspicuity* of items and do not pay explicit attention to other parameters such as lightness, brightness, luminance, or luminance contrast. Blob luminance of the test pattern was initially set to minimal contrast. In this case, the blobs of the reference pattern usually appeared far more salient than the blobs of the test pattern. By increasing blob contrast, subjects could make the test pattern more salient than the reference pattern, and reverse this ranking again by decreasing blob contrast. They were encouraged to take their time and move blob luminance above and below the percept of equal salience to ensure that they had indeed matched salience, not other stimulus properties. While the first adjustments took quite a while and several returns, after some praxis subjects could perform the matching task faster, with highly reliable results. However, certain stimulus pairs were more difficult to match than others.

While most luminance adjustments could be made so that subjects were satisfied with the result, a number of test conditions had required adjustments beyond the monitor limits so that subjects had to finish the trial even though an optimal match could not be reached.

Subjects

The majority of experiments were performed by two (female) students each 22 years at the beginning of the project, who were paid for the time in experiment, and the author (male; 56 years). Experiments 7 and 8 were added later and performed by two new observers (one male, one female) of 32 and 34 years, respectively, and the author (then 65 years). All subjects had normal or corrected-to-normal visual acuity. While the author had long-lasting experience with stimuli of this sort, none of the other observers had seen these stimuli before or was familiar with the scientific background and the aim of the study. The author, though intended to find a systematic rule of how salience can be quantified, was not biased to a particular model beforehand.

Data Analysis

Salience adjustments were registered by storing the final computer settings of each adjustment. Before averaging and further analysis, these values were converted into luminance data by interpolation of an exponential fit to 14 offline measurements over the full luminance range of the tests. To take care of (small) stray light effects in the display, different such fits were used for different background settings; all data had been obtained in careful and repeated luminance measurements of blobs on different backgrounds. The deviations of blob luminance between the lowest and highest background were ≤ 1.2 cd/m^2 on the standard monitor; this maximum shift was only obtained for the darkest blobs presented on the brightest background. The resulting luminance settings from different adjustments were finally accumulated and averaged.

RESULTS

In order to understand salience computation from luminance one would like to know how salience changes when background or target luminance is varied and how different targets (bright or dark) are related in their salience. I have addressed these questions in altogether eight experiments. In seven of them, subjects were asked to adjust similar (sections I and II) or dissimilar targets (section III) on different backgrounds so that they appeared equally salient to the observer. In the last experiment, subjects were asked to review given pairs of stimuli and evaluate whether the targets appeared equally salient or not (section IV).

Note however that the section numbers and the numbering of experiments do not resemble a temporal sequence in which the experiments had been performed; they are only used to structure presentation. Data collection from different experiments was made in interleaved sequences.

I. EQUAL-SALIENCY MATCHES OF DARK OR BRIGHT BLOB ARRAYS

This section includes three experiments, in which blob arrays of equal lightness were compared, dark blobs with dark blobs, and bright blobs with bright blobs. In each of these experiments, subjects saw a large collection of test stimuli and always had to match the salience of blobs in one half of the stimulus (“test pattern”) to that of blobs in the other half (“reference pattern”). Luminance settings were varied to cover a large range of conditions within each test category.

Experiment 1: Equal salience of dark blob arrays

Look at Figure 1 and consider what would happen when you change illumination. Intuitively you might expect that the salience of blob patterns will not change – and that is by and large the result of Experiment 1.

Method

The experiment included five test series. In each series, a fixed reference pattern (grey symbols in Fig. 2) was compared with 8 test patterns (black symbols) at different background luminance (open circles). Subjects had to adjust blob luminance in the test pattern (filled black circles) to make blobs equally salient as blobs in the reference pattern (filled grey circles). The five test series differed in the contrast (luminance) of the reference blobs.

Results and Discussion

After some initial training subjects reported having no difficulties to perform the task and reliably adjusted blob

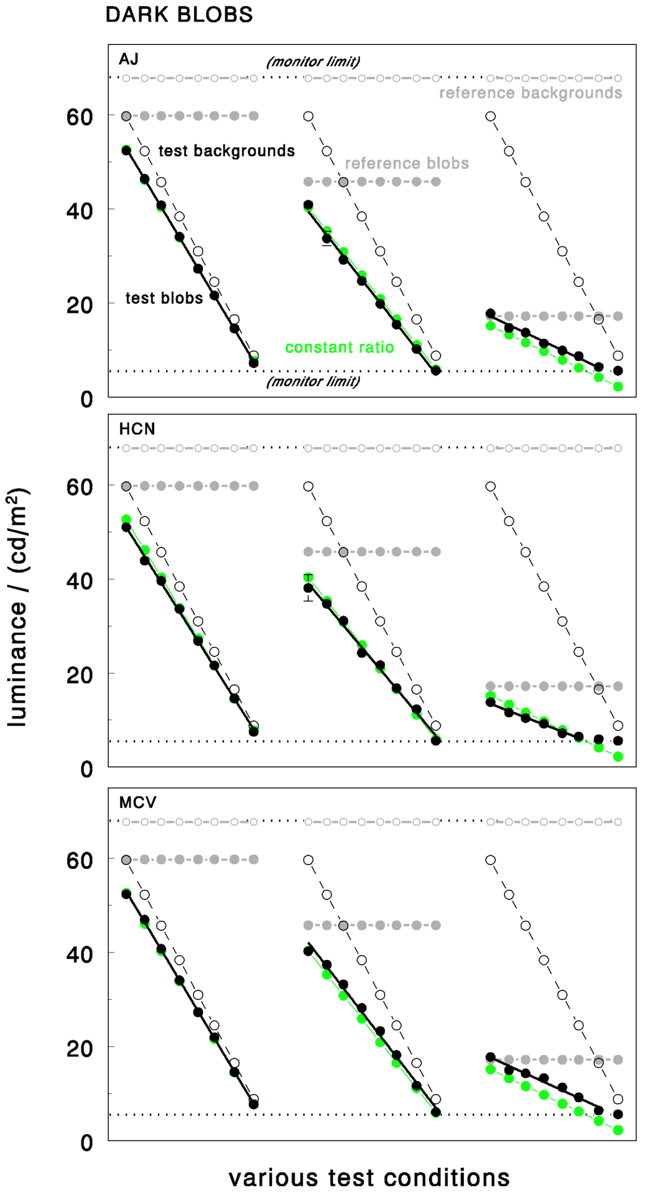

Figure 2. *Equal-salience matches with dark blobs (Experiment 1).* Data from three test series (left-hand, middle, and right-hand curves) are shown for three subjects (rows). Within each test series, reference patterns (grey symbols) were held constant and test patterns varied (black symbols). For different backgrounds (open circles), test blobs (filled black circles) were adjusted until they appeared similarly salient as the reference blobs (filled grey circles). Data show averages of 2-6 adjustments with the s.e.m. (if larger than symbols). Adjustments closely follow predictions for a constant luminance ratio of blobs and backgrounds (green circles), with certain deviations. Luminance settings of the monitor were limited to 5.5 – 68 cd/m^2, as indicated by dotted lines.

luminance in the test patterns. The matches from three test series at low, medium, and high target contrast are shown in Figure 2. There was only little variability across repeated adjustments (s.e.m. was typically smaller than symbols) and data from the three subjects look rather similar (Fig. 2a, b, and c).

In comparison to the reference conditions with high background luminance, test blobs had to be dimmed when the background luminance was decreased. The required dimming was proportional to the reduction of background luminance between reference and test patterns. Predictions from strict proportionality ("constant ratio") are indicated by green circles; most matches fell close to these predictions. Thus, on a first view, equal salience was obtained for a constant ratio of target and background luminance. But the data also show deviations from this rule, in particular in the right-hand test series in Figure 2 with the largest blob contrast tested.

Experiment 2:
Equal salience of bright blob arrays

An analogous experiment was performed with bright blobs on dark backgrounds.

Method

The final version of this experiment included seven test series. In each series, reference patterns were held fixed and compared with 3-7 test patterns at different background luminance. Test series differed in the contrast of reference blobs.

Results and Discussion

Data from four test series of each subject are shown in Figure 3. In the reference patterns (grey symbols), blob luminance (filled circles) was always high and background luminance settings (open circles) varied from high to low between the series. When matched with test blobs on dimmer backgrounds (black symbols), blob luminance had to be reduced to maintain the same salience level. Constant-ratio predictions are again indicated by green circles. By and large, the equal-salience matches fell close to these predictions, but deviations were sometimes pronounced, particularly when the blob contrast in reference pattern was large (right-hand data curves, labels "1" and "2"). Although there was little variation in repeated matches by the same subject (generally small s.e.m.), the matching performance in certain test series varied considerably between subjects.

According to Stevens (1961; Rudd & Popa, 2007), brightness perception follows a power function of luminance with an exponent $x = 0.33$. Predictions based on equal differences of the power-transformed blob and background luminance settings are shown by red circles in Figure 3. These predictions nearly overlap the constant-ratio predictions (green) in the left-hand test series, but differ notably in the labeled test series on the right-hand side of each graph, where the two predictions seem to reflect the variations seen in the data of different subjects. For example, the matches of data series "1" by subject AJ fall closely upon the power-transform predictions (red), whereas those by subjects HCN and MCV tend to follow the constant-ratio prediction (green). With series "2", preferences change; now the data of HCN follow the power-transform and those of AJ and MCV more closely the constant-ratio rule or lie in between.

Before looking at these variations in more detail, the similarity of equal-salience matches with bright and dark targets (Exp.1 and 2) should be underlined. In both experiments, blob luminance had to be decreased by the same proportion by which background luminance was decreased, to hold blob salience constant. This is visualized in Figure 4, which summarizes the findings of Experiments 1 and 2.

Data points (filled circles) represent the adjustments of blob luminance (ordinate) on various background settings (abscissa) when blob salience was matched to that in a given reference pattern (open circles); for each test series a regression line (thick continuous) is fitted to the data. Tests with dark blobs on brighter backgrounds (Exp. 1) fall into the lower-right halves of the graphs, tests with bright blobs on dimmer backgrounds (Exp. 2) into the upper-left halves. For easier distinction, data from different test series are alternately colored black and gray. Different curves (obtained with different reference patterns) represent different blob salience. All curves point towards the origin.

Two different predictions are plotted into these data. Green lines (Fig. 4a) show the expected matches if equal salience was based on the constant-ratio principle, *target/background = constant*. Red lines (Fig. 4b) predict

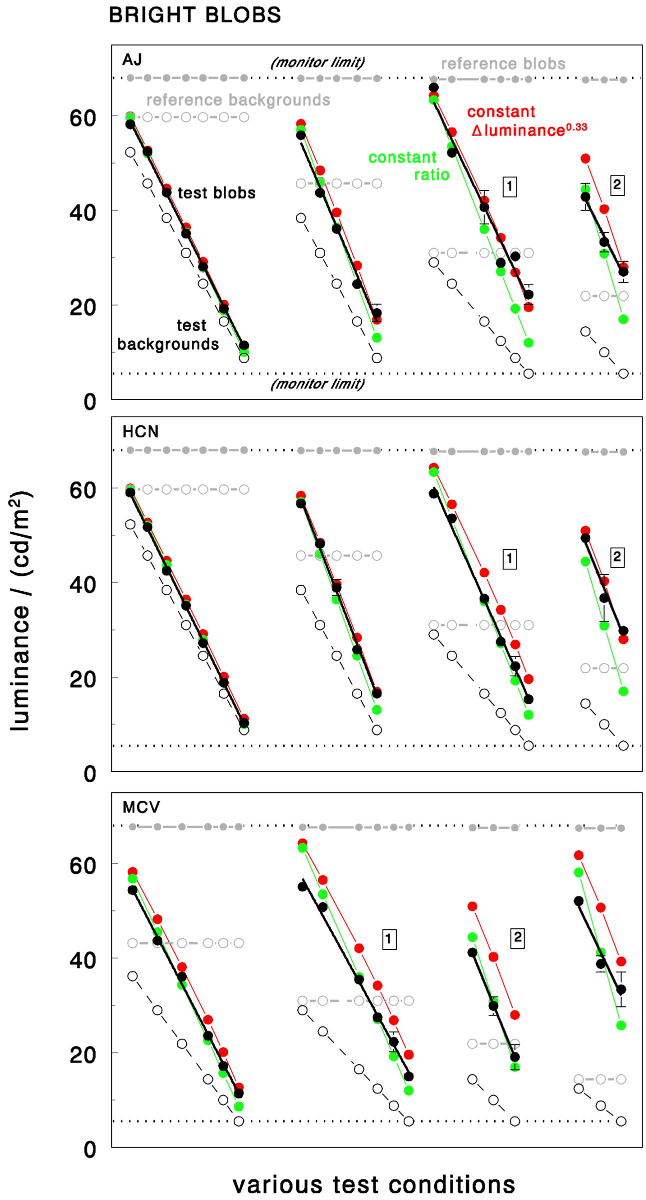

Figure 3. *Equal-salience matches with bright blobs (Experiment 2).* Symbols as in Figure 2. Adjustments again follow the constant-ratio rule (green circles) and sometimes Stevens' brightness law (red circles; predictions based on constant differences of blobs and backgrounds in the power of luminance, exponent x=*0.33*). Deviations from either prediction are sometimes pronounced. Number labels are referred to in the text.

the matches if equal salience would be obtained for constant differences of the power-transforms (exponent

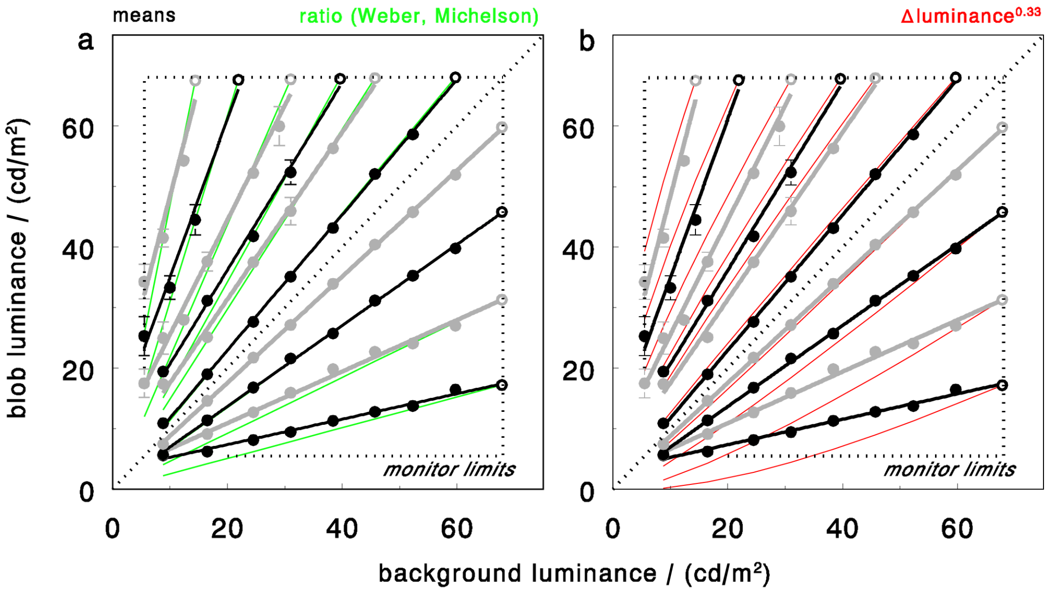

Figure 4. *Summary of equal-salience matches in Experiments 1 and 2.* Adjusted blob luminance is plotted against the according background luminance when test blobs (filled circles) appeared equally salient to reference blobs (open circles). Data of different test series (colored alternately grey and black for better distinction) are fitted by regression lines (thick continuous) and compared with two predictions, the constant-ratio rule (green) and Stevens' brightness law (red). **a.** Green lines show the expected adjustments if equal salience is perceived for a constant ratio of blob and background luminance. **b.** Red lines show the expected adjustments if equal salience is obtained for constant differences in the power of luminance (exponent $x=0.33$). Curves by and large follow the constant-ratio principle *(a)* with notable deviations towards flatter curves in certain test series.

$x = 0.33$) of blob and background luminance, $|target^{0.33} - background^{0.33}| = constant,$ according to Stevens' brightness law. Obviously, the predictions from Steven's brightness law (Fig. 4b) deviate strongly from the data, in particular for dark blobs, and only the constant-ratio predictions (Fig. 4a) provide a reasonable fit. There are, however, still notable deviations that will be further investigated in section II.

While the general performance in Figure 4 might be impressive, it is important to stress a peculiarity with bright blob matches in Experiment 2. Note that in all matches of Figure 4, the blobs in the reference patterns (open circles) were the brightest items in the display, and all test blobs to be adjusted were less bright than these. Earlier test series with dimmer reference and brighter test blobs had produced quite different and sometimes variable and inconsistent results (Fig. 5). In these series, equal-salience matches often followed the constant-addition rule, as revealed by the similar slopes of regression lines through the data, which all varied around *m=1.0*. That is, the brightest blobs appeared similarly salient as less bright blobs if luminance *differences*, not ratios, to the according backgrounds were identical. The resulting pattern is quite different from the constant-ratio performance in Figure 4. Two curves (green and magenta) reveal a mixture of both strategies; some subjects performed matches along the constant-addition rule, others made a few constant-ratio adjustments for the dimmest bright targets and then switched to constant addition for the brighter targets. As a result, the mean data show an initial increase (and a local deviation from constant addition) but flatten with further increasing background luminance; the s.e.m. may be strongly increased.

This surprising matching behavior can likely be explained by two effects; a generally increasing tolerance and hence "uncertainty" of matches at high luminance (studied in Experiment 3) and a slow process of anchoring of the visual system to the brightest stimuli in a scene (Anderson, Singh, & Meng, 2006). In the present study, the equal-salience matches of bright blobs were found to be easier, and the results more reliable, when the reference blobs were the brightest items and the test blobs to be adjusted were dimmer than these. These arrangements were then used in the final tests of Experiment 2.

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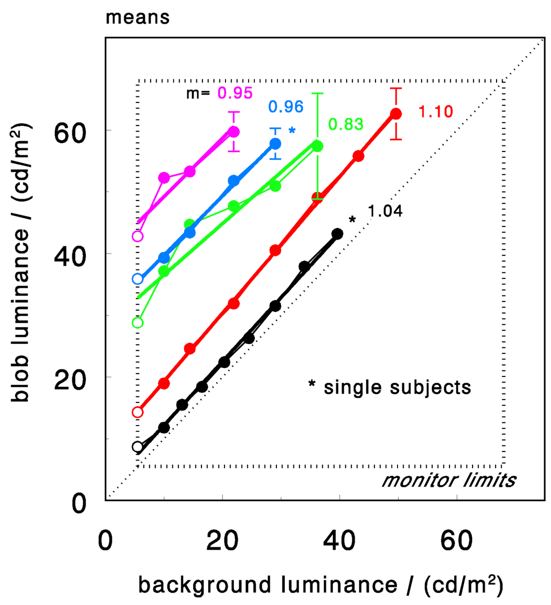

Figure 5. *Different matching curves when test blobs were the brightest items.* Test series with bright blobs (Experiment 2) obtained with dimmer reference blobs (open circles); averaged performance of three subjects (except curves marked with *). Equal-salience matches in these patterns were often more variable and could strongly vary between subjects; error bars show the mean s.e.m. of all data points in a curve. Different to Figure 4, performance did not follow the constant-ratio rule but more closely the constant-addition rule (constant luminance difference between blobs and background), as verified by the slopes around $m=1.0$.

Experiment 3: Tolerance ranges of equal-salience matches

Although Figure 4 shows no systematic difference between dark and bright blobs, matches of bright blobs (Exp. 2) were generally less precise than matches of dark blobs (Exp. 1). Subjects sometimes reported a gradual uncertainty when matching very bright, but never when matching dark blob arrays. While, with dark blobs, their salience rating of the test and reference blobs was clearly reversed when they increased or decreased test blob luminance beyond the equal-salience point, they reported that, with bright blobs, they could continue increasing or decreasing blob luminance over a considerable range before noticing a clear reversal of the salience ranking.

To quantify this observation, three test series of Experiments 1 and 2 were repeated and, in separate runs, subjects were asked not only to match the blobs in salience but also to adjust them so that either the test blobs or the reference blobs were just more salient.

Method

Test series were run three times, with different instructions. In one run, subjects matched the two patterns in salience, as before. In two additional runs, subjects were asked to adjust test patterns so that blobs were either just a little more, or just a little less salient than the blobs in the reference pattern.

Results and Discussion

This created, for each subject and for each of the selected test series, two additional curves representing the upper and lower *tolerance level* in salience adjustments (Fig. 6a, b; grey), which can be compared with the true equal-salience matches of the third curve (black). As can be seen, tolerance ranges strongly increased with the blob luminance of the according match. This was similarly found for dark and bright blobs (Fig. 6a) and with all subjects (Fig. 6b). Since the paradigm depends on a decision criterion individually set by each observer, tolerance ranges may differ. But subjects have likely not changed their criterion between the different matches of a test series (and probably not between series either), therefore the general observation is reliable. When all data from a subject are superimposed and plotted against the matched blob luminance, values of different test series fall upon similar regression lines (Fig. 7a). This indicates that tolerance variations are not the result of a particular salience match or reference pattern.

Some graphs in Figure 7a show a systematic asymmetry between the upper and lower tolerance branches. This asymmetry cannot be due to a systematic bias between test and reference patterns, since the branches refer to different rankings with bright and dark blobs. The “inner” curves (curves closer to the oblique midline in Fig. 6) represent test blobs with smaller contrast (appearing less salient) than the reference blobs; the “outer” curves represent test blobs with larger contrast (appearing more salient) than blobs in the reference patterns. These rankings are mixed up when data from bright and dark blobs are superimposed (Fig. 7a) but the asymmetry remains. For a just notable salience difference, blobs brighter than the best matches

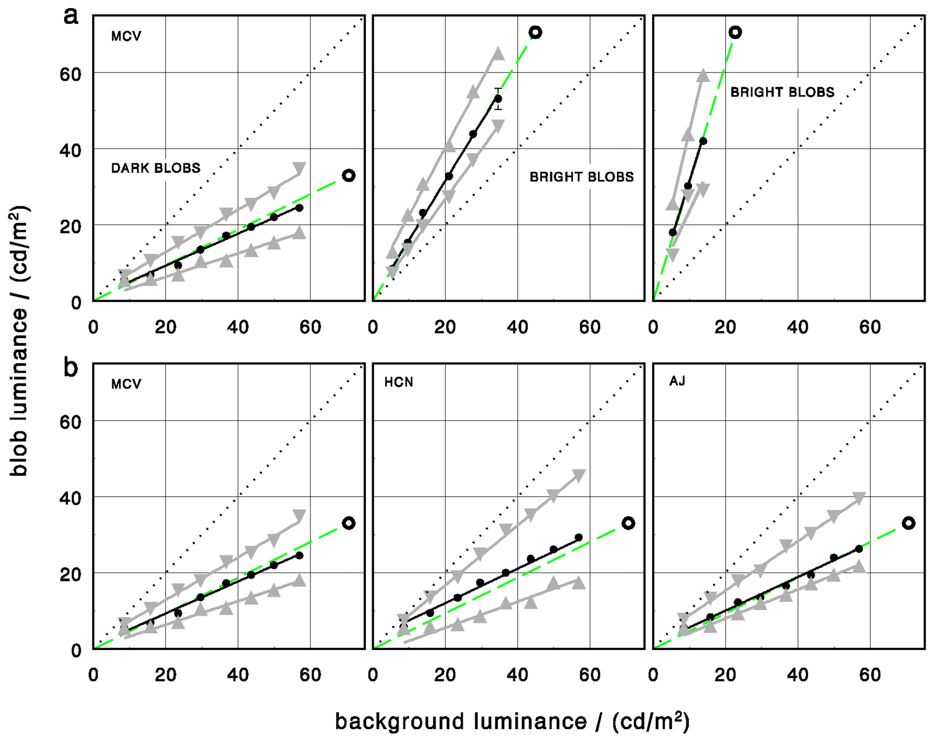

Figure 6. *Tolerance of salience adjustments.* In different runs, subjects indicated when targets matched in salience (filled circles; black), or when one, or the other, blob array was just notably more salient (grey symbols). Data are fitted by regression lines. Reference patterns were constant over a test series (open circles) and data points show the adjusted blob luminance for various test pattern backgrounds. Predictions for the constant-ratio rule are plotted in green. **a.** Different test series from the same subject, one on dark, two on bright blobs. Tolerance ranges generally increase with the luminance of matched blobs. **b.** Same test series performed by different subjects. Tolerance ranges increase with all subjects but at different degrees. Note the asymmetry between dimmer and brighter blobs that are just less or more salient than reference blobs; the difference was pronounced in some tests.

(midline) had to be more increased in luminance than blobs darker than the best matches had to be decreased. This asymmetry is seen with both dark and bright blobs (dark and grey symbols, respectively) and thus independent of the perceived lightness of blobs.

Both the asymmetry of curves and the increasing tolerance range (with increasing match luminance) likely reflect the power function of visual sensitivity known as “Stevens' brightness law” (Rudd & Popa, 2007). If this is true, accordingly transformed data should fall upon parallel lines and the asymmetries between the upper and lower tolerance range should disappear. This was approximately the case for all subjects for a power transform with an exponent of $x=0.33$ (Fig. 7b), in good agreement with Stevens' brightness law.

The essentials of Figures 6 and 7 are summarized in the grand total in Figure 8, in which the data from all subjects are superimposed. Although the subjects' individual criteria might have differed, the increasing tolerance range with increasing blob luminance and the asymmetry of tolerance branches are quite obvious (Fig. 8a). Both almost disappear when luminance scales are power-transformed (Fig. 8b).

Although there were no principle differences between dark and bright blob matches (Fig. 8), these observations may nevertheless explain why matches of bright blobs (Exp.2) appeared more difficult and were generally more variable than matches of dark blobs. Since the bright blobs in Experiment 2 were, on average, brighter than the dark blobs in Experiment 1 (and the variations of particularly

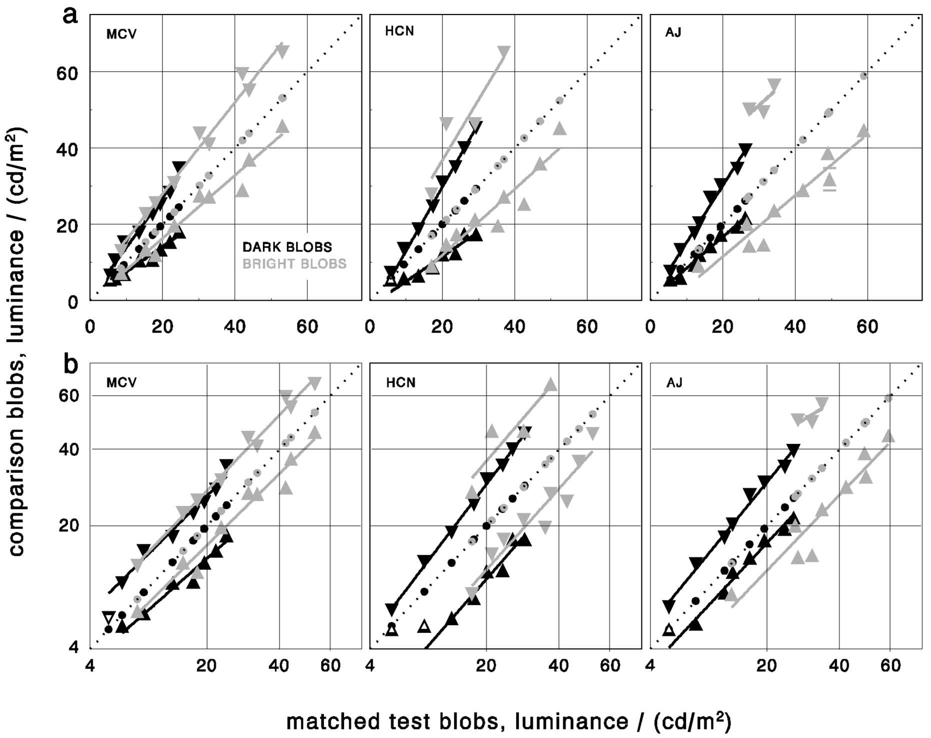

Figure 7. *Accumulated tolerance measurements from different test series.* **a.** Superimposed data of all tests series from a subject, plotted against the (equal-salient) matched test blob luminance; data from dark blob matches are shown in black, those from bright blob matches in grey. Data represented by open symbols were likely affected by monitor restrictions and are not included in the computation of regression lines. The increase of tolerance ranges with increasing blob luminance is a general effect and does not depend on test series or the contrast polarity of blobs. **b.** Same data when luminance is scaled to a power function with exponent $x=0.33$ (Steven's brightness law). Tolerance ranges now appear almost constant, and the asymmetry between dimmer and brighter blob patterns has largely disappeared.

bright dark blobs was also restricted by the nearby background settings), they should have suffered more from the increasing tolerance ranges in equal-salience matches than dark blobs.

Discussion of Section I

Experiments 1 and 2 provide strong evidence that luminance-defined salience is primarily related to the luminance ratio of targets and backgrounds. This holds for dark and bright targets. Over a wide range of background settings, blobs appeared as similar salient when their luminance *ratio* to background was constant. Very bright blobs, however, may also appear as equally salient when their luminance *difference* to background is constant. This was often observed when brighter blobs were adjusted to match the salience of less bright blobs but never the other way around.

Matching difficulties

As already mentioned, these observations may be explained by two known phenomena, Stevens brightness law (Stevens, 1961; Rudd & Popa, 2007), which has made adjustments of very bright targets less certain, as shown in Experiment 3, and the especial role of the brightest items in a scene as an "anchor" for brightness estimates (Anderson, Singh, & Meng, 2006; for general descriptions of the anchoring theory and later modifications see Gilchrist et al., 1999; Bressan 2006a, b; but see, for example, Anderson, Whitbread, & de Silva, 2014; Blakeslee, Reetz, & McCourt, 2009; Maniatis, 2014; Rudd & Zemach, 2005, for counter-examples, critics, and

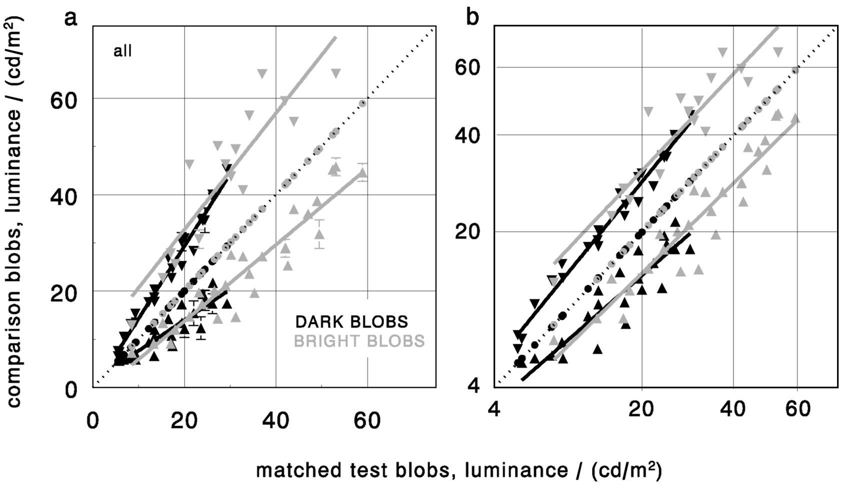

Figure 8. *Grand total of tolerance measurements in Experiment 3.* Data from all subjects superimposed; dark blob comparisons in black, bright blob comparisons in grey, with the according regression lines. In spite of the different criteria applied by each subject (cf. the different ranges in Figure 6b), the grand total reveals the major effects. **a.** Tolerance ranges (in which one blob pattern is not notably less or more salient than the other one) increase with blob luminance; there is no principle difference between dark and bright blobs, but an obvious asymmetry between blobs darker (less bright) and blobs brighter (less dark) than the comparison blob. **b.** In the power transforms of the data (exponent $x=0.33$) tolerance ranges appear more constant and the asymmetry is (almost) gone.

alternative theories). The less brisk salience reversals with bright blobs might have misguided subjects to accept settings even when the blobs were dimmer than predicted by the constant-ratio rule. The problem did not occur when reference blobs were the brightest elements and only dimmer luminance settings had to be adjusted. Anderson, Singh, and Meng (2006) have reported similar problems; their subjects could not reliably adjust the brightest luminance setting in a scene but were fairly accurate on the adjustments of dimmer luminance settings. The authors took this as evidence that the visual system performs brightness matches on the basis of an anchoring process to the brightest luminance setting available. They found that the dynamics of this anchoring process is rather slow so that it may take several minutes to settle to a new level—a time course much slower than a single salience match usually took in my experiments.

I do not want to stress the anchoring issue here too much. It is widely disputed in the context of brightness and lightness estimates, which both may be different from the salience matches performed in the present study. The observation does, however, suggest that brightness effects might be more important in salience matches than the pure existence of a luminance difference between targets and background. I will address this aspect further in Experiments 4 and 5.

Salience variations

Another important point to mention with the graphs of Figure 4 is the variation of target salience with the slopes of curves. Curves close to the diagonal (slope $m=1$) are from test series with low pattern contrast and little target salience, while curves with steeper (bright blobs) or flatter slopes (dark blobs) are from test series with higher pattern contrast and hence more salient blobs. Note that the constant-ratio rule leads to a "compression" of salience variations under low illumination, where small luminance differences modulate target salience more strongly than under high illumination. For dark blobs, the maximally achieved contrast would be that of targets at zero luminance (corresponding to zero reflection). According to the constant-ratio rule, such targets (which could not be realized in the experiments) should be similarly salient on all backgrounds (slope $m=0$). We do not yet know, how slopes with $m<1$ (dark blobs) and slopes with $m>1$ (bright blobs) relate to each other in terms of salience; this will be studied in Experiments 6 and 7 (section III).

II. EXCURSE ON SLOPE DEVIATIONS

While the constant-ratio rule seems to be a good approximation to explain the equal-salience matches in Experiments 1 and 2, closer inspections of the data in Figure 4a reveal notable deviations. Many curves are slightly flatter than predicted. The deviations are small for curves close to midline and more pronounced with the steeper or flatter curves obtained with larger target contrast. The possible origin of these deviations is the topic of this Excurse. I will begin with excluding some intuitive suspicions.

Contrast effects that cannot explain the observed slope deviations

Contrast definition. First of all, the constant-ratio principle (and deviations of it) is not dependent on how luminance contrast is computed. Let *tg* and *bg* represent target and background luminance settings, respectively. Independent of whether salience is related to Weber contrast

$$salience \sim \frac{|tg - bg|}{bg} \qquad \text{(Weber contrast)}$$

or Michelson contrast

$$salience \sim \frac{|tg - bg|}{tg + bg} \qquad \text{(Michelson contrast)} ,$$

the equal-salience conditions for two blob arrays,

$$\frac{|tg_1 - bg_1|}{bg_1} = \frac{|tg_2 - bg_2|}{bg_2} \qquad \text{(W1)}$$

and

$$\frac{|tg_1 - bg_1|}{tg_1 + bg_1} = \frac{|tg_2 - bg_2|}{tg_2 + bg_2} \qquad \text{(M1)} ,$$

are both transformed to

$$\frac{tg_1}{bg_1} = \frac{tg_2}{bg_2} \qquad (1)$$

which is the constant-ratio rule.

Stray lights. Stray light effects on the screen have been measured and were found to be small (<1.8%, see General Methods). This does, however, not exclude the possibility of stray light effects inside the eye. Let us briefly consider what should have happened if stray light effects had been strong in these experiments. Whether the light of a bright blob would partially spread into the surround, or light from a bright surround would partially spread into a dark blob, the major result would be a (linear) attenuation of target contrast. Instead of seeing reference patterns at the measured (and plotted) luminance conditions, the perceived contrast of the reference patterns would be smaller, as sketched in Figure 9a. Thus, for the *perceived* conditions (open circles), the constant-ratio rule would result in a different slope (*b=a'*; dashed) compared to that for the *measured* conditions (*a*; continuous).

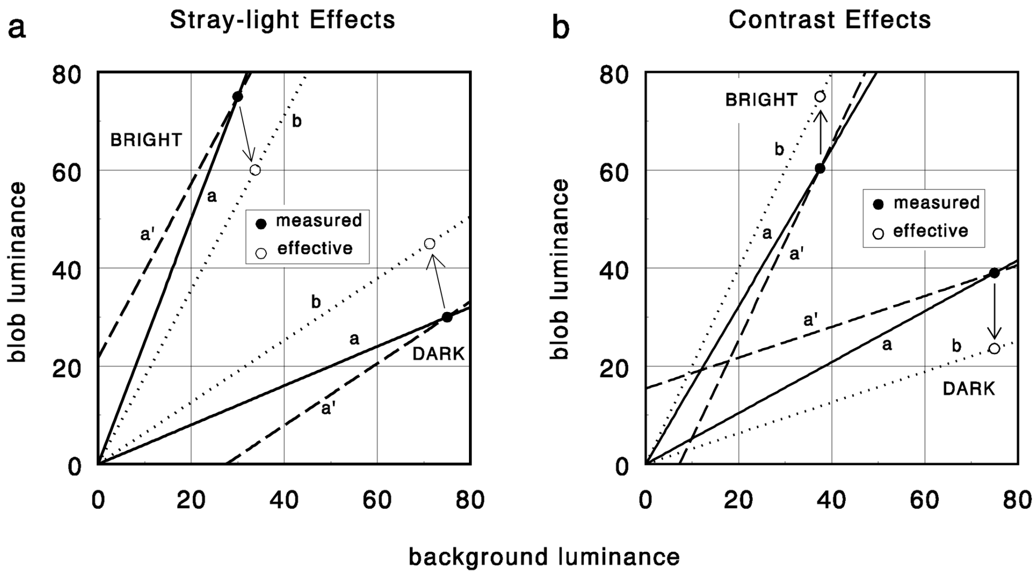

Figure 9. *Schematic drawings of artifacts that cannot explain the slope deviations in Figure 4.*
a. Stray-light effects. **b.** Contrast enhancement. If the measured luminance settings of reference patterns (filled circles) had been modified by these effects (open circles), constant-ratio settings (continuous lines) should have resulted in different slopes (dotted and dashed lines). Both effects could only explain deviations for one type of patterns (dark blobs or bright blobs) and thus cannot account for the similar slope deviations seen with dark and bright blob matches in Figure 4. Furthermore, they should have also affected the appearance of *test* blobs so that any distortions (if present) would have largely been compensated (see text for details).

There are two reasons why these effects cannot explain the observed slope deviations in Experiments 1 and 2. First, while the expected slope changes would be consistent with the observed deviations for *bright* blobs (curves were indeed flatter than predicted, cf. dashed vs. continues curves), slopes of dark blobs should have changed in the opposite direction. In fact, however, all measured curves were flatter, not steeper than predicted from constant ratio (cf. Fig. 4). Second, since the process is linear, not only the reference but also the test patterns should have been affected. Thus, all data points should be re-scaled, so that the stray light effects in reference and test patterns would finally compensate.

Mathematically, stray light effects can be added by increasing the measured luminance data *(tg, bg)* by a linear proportion of light from the other regions. The corrected luminance settings would then be

$$tg' = tg + \alpha \cdot bg$$

$$bg' = bg + \alpha \cdot tg$$

with $0 \leq \alpha < 1$. When these replacements are substituted in equation *(1)*, the constant-ratio rule will not be violated.

Contrast enhancement. Several neural processes modulate the *apparent* contrast of visual stimuli. Some of them, like lateral inhibition, are already implemented at early processing stages. Functionally, they enhance the contrast so that it appears to be stronger than computed from the luminance measures. By means of lateral inhibition, the contrast of reference patterns in Experiments 1 and 2 should have appeared larger than reflected by the data points in Figure 4. This is sketched in Figure 9b; contrast enhancement would make the bright blobs appearing brighter and the dark blobs appearing darker than luminance measures indicate (arrows). As a consequence, the constant-ratio rule would then require the salience-matched test conditions to lie on a steeper (bright blobs) or flatter curve (dark blobs) than predicted from the measured data (slopes $b=a'$ instead of a).

Like stray light, however, the effect could only explain the slope shifts for one target polarity. The flatter slopes predicted for dark targets would be consistent with the experimental observations, the steeper slopes predicted for bright targets would be opposite to them. Furthermore, there is no reason why contrast enhancement should only occur with reference patterns and not also with test patterns. If we assume that its strength were linearly related (which is not entirely correct) to the luminance difference between blobs and background, the resulting slope shifts would be cancelled (as described for stray light effects in the previous section). Thus, contrast enhancement, too, cannot explain the observed slope deviations from the constant-ratio rule.

To prove this mathematically, we must replace the measured target luminance, *tg*, in the above equations by a value that would correct for the assumed contrast enhancement effects. If the underlying mechanism were lateral inhibition and mostly linear, the neural response could be approached as a combination of excitation from the target and inhibition from the surround. Contrast enhancement can then be given as the difference between the response to a homogeneous field at target luminance (no contrast = full inhibition from surround) and the response to the real stimulus with reduced inhibition (increased contrast). The following description is for bright blobs on dark background; by assuming that bright and dark blobs are represented by on center and off center cells, respectively, responses to dark blobs can be treated in a similar way. If the strength of inhibition is linearly related to the luminance in the surround, *surr,* the response, *resp,* can be described as

$$resp \sim tg - \alpha \cdot surr = k \cdot (tg - \alpha \cdot surr)\ ,$$

with a proportionality factor, *k,* and the inhibition factor, α ($0 \leq \alpha \leq 1$). The true response to a bright target under contrast *(bg < tg),*

$$resp_{\ tg\ (contrast)} \sim tg - \alpha \cdot bg = k \cdot (tg - \alpha \cdot bg)\ ,$$

would then differ from the assumed response to a non-contrasting target *(surr = tg)*,

$$resp_{\ tg\ (no\ contrast)} \sim tg - \alpha \cdot tg = k \cdot (tg - \alpha \cdot tg)\ ,$$

which was used to predict the constant-ratio slopes from measured luminance settings. The *difference* is linearly related to the luminance difference between targets and background,

$$\begin{aligned} resp_{\ tg\ (contrast)} - resp_{\ tg\ (no\ contrast)} \\ &= k \cdot (tg - \alpha \cdot bg) - k \cdot (tg - \alpha \cdot tg), \\ &= k \cdot \alpha \cdot (tg - bg)\ . \end{aligned}$$

Thus, to include contrast enhancement in our computations, we should replace the measured target luminance, *tg,* by a value, *tg'*, that corrects for this difference,

$$tg' = tg + \alpha \cdot (tg - bg)\ ,$$

(the proportionality factor, *k,* which links responses to luminance settings, would similarly apply to *tg'* and *tg*, and hence can be left out).

If this *tg'* is used instead of *tg* in equation *(1)* and values are substituted, the additional corrections for target *1* and target *2* will compensate and the constant-ratio rule *(1)* still holds.

In search of another explanation

The conclusion that the observed deviations from the constant-ratio rule are not explained by measurement artifacts is helpful but does not answer the question where the deviations come from. A number of additional tests which were run to reproduce or modulate these deviations have raised a suspicion; this suspicion was followed up in the following experiments.

Effects from stimulus brightness. The suspicion was that target salience is not only defined by stimulus contrast but also by the apparent lightness and brightness of contrasting targets. While subjects (when accordingly instructed) could match two blob arrays to display similar *contrast* to the surrounding background (and then produced data consistent with the constant-ratio principle), the adjusted luminance setting did not always make blobs look similarly conspicuous. Thus, when required to match blobs for *salience* (the standard instruction in this study), subjects felt they had to correct these previous adjustments. The need for corrections was particularly pronounced for (bright and dark) blobs at high contrast where the strongest deviations from the constant-ratio rule were observed (Fig. 4).

The difference can be visualized in the pattern sequence of Figure 10. (If luminance variations in the figure do not adequately show up in the print-out, please try a different printer or view the figure on a monitor.) One half of each pattern and the background of the other half are held constant; blobs in the second half are varied in contrast (thus, in principle, resembling the adjustment process subjects had performed with each match). While blob salience clearly fails to match in the first and the last pictures of the sequence, there is some uncertainty in the middle pictures. When comparing individual blobs and looking for patterns with similar *blob contrast* to background, one would probably select the pictures around (c), (d), and (e), in which the blobs appear also similarly salient in their local surroundings. But when searching for patterns in which targets are *globally identical*, one would probably chose patterns (g) or (h), in which all blobs of the pattern appear more similar in lightness and brightness. These estimates are also affected by the many other visual cues in the pattern, like the spatial configuration and the contrast between backgrounds; therefore, the global impression of similar blob lightness may be different from a careful brightness

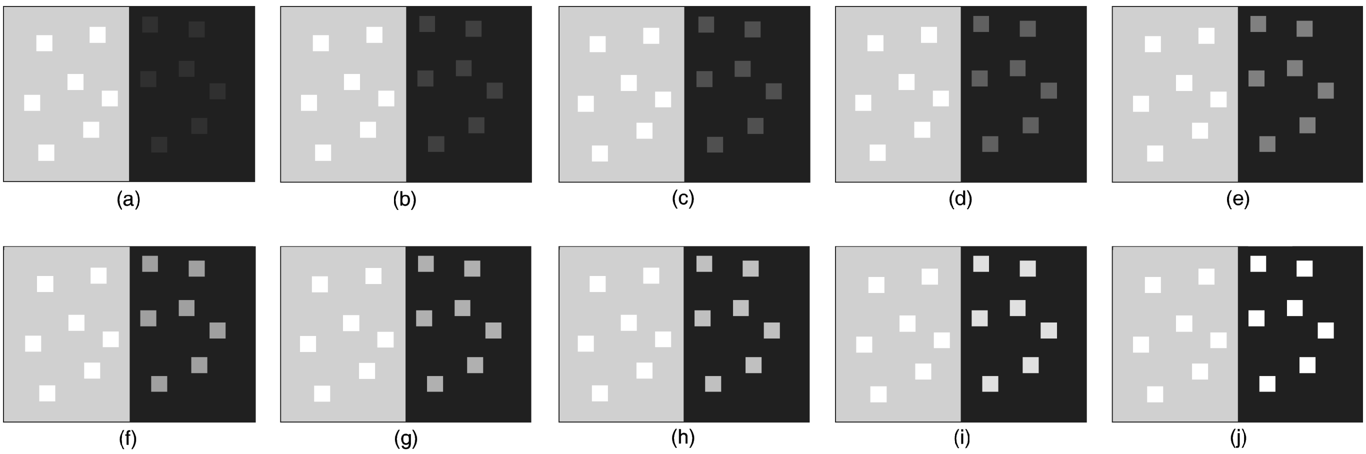

Figure 10. *Illustration of different equal-salience decisions.* The left-hand side blob patterns in all pictures are identical; in the right-hand side patterns blob luminance is increased from (a) to (j). Looking at different patterns is comparable to an equal-salience match performed in the experiment. The reader is asked to find out which blob arrays match best in salience, which in local contrast, and which in brightness. You may have to view the figure on a monitor, if grey levels do not properly reproduce on your printer.

match of single blobs under foveal inspection, which would probably be obtained in (i) or (j). Only in (j), however, have blobs identical luminance.

This demo illustrates that the percept of equal salience is not only related to stimulus contrast but also affected by aspects of target similarity and target brightness. The interference appeared to be stronger in simple patterns than in complex scenes where the surround is "articulated" (Schirillo, 1999a, b) and was felt to be particularly strong with single blobs. Brightness and lightness perception is strongly influenced from a large number of variables, such as simultaneous contrast, target size, assimilation, surround "articulation", interpretation of the material and of the scene, etc. (Adelson, 1973; Arend & Goldstein, 1987; Barkan, Spitzer, & Einav, 2008; Blakeslee & McCourt, 2004, 2012; Bressan & Kramer, 2008; Bruno, 1994; Bruno, Bernardis, & Schirillo, 1997; Gilchrist, 1988; Gilchrist, Delman, & Jacobsen, 1983; Logvinenko & Ross, 2005; Robilotto & Zaidi, 2006; Schirillo, 1999a, b).

Additional Experiments

These observations raised the question of whether one could modulate the influence of such effects in actual tests. That was studied in two experiments. In Experiment 4, a variation of stimulus conditions and matching instructions was found to modulate the strength of deviations from the constant-ratio rule. In Experiment 5, the influence of a typical brightness modulation effect, assimilation, was studied in salience matches. The results show that lightness and brightness effects may strongly affect the measures of salience matches but can partly be excluded under certain circumstances.

Experiment 4: Modulation of brightness effects in salience matches

To see if matches could experimentally be biased to either follow the constant-ratio slopes or produce strong deviations towards brightness matching, I have performed a series of tests several months after the data collection in Experiments 1-3 was finished. In different test series on similar stimuli, performance was biased to favor either a match for target conspicuity (salience) or a match for target similarity.

Method

Measurements were restricted to four test series of Figure 4, two on bright and two on dark blobs, in which notable deviations from the constant-ratio rule had been observed. Each of these series was run in three versions (cf. Fig. 11), with a reference pattern at maximum background luminance as in Experiments 1 and 2, and in addition with reference patterns at medium or low background luminance settings along the expected constant-ratio curves (large circles). If performance would follow the constant-ratio principle, data points from different curves should fall upon one line. However, if performance was affected by the apparent brightness of blobs, the matches on different curves might be displaced since the targets in different reference patterns had different brightness due to brightness induction from the different backgrounds.

All test series were run, in alternating sequence, under three different conditions. In *condition A*, referred to as *peripheral salience match*, patterns were inspected parafoveally and peripherally with the gaze being directed to midline positions between and above or below the two patterns. To facilitate these gaze directions, a number of fixations points along the midline were drawn upon the hard-paper mask. Adjustments were made so that the blobs in both patterns appeared similarly brisk and conspicuous and tended to loose their conspicuity at the same (vertical) eccentricity when the observer's eyes were moved up and down. Stimulus patterns tested in this condition displayed the standard arrays with two 3x5 blobs on either side of the screen; blob size was slightly increased (see below). Stimuli were looked at through a hard-paper mask, as in Experiments 1-3. In *condition B*, referred to as *global lightness match*, targets were inspected parafoveally with the gaze in the middle between both patterns and luminance was adjusted so that all targets appeared similarly light. To strengthen lightness effects in this task, the hard-paper mask was removed so that the luminance contrast of the two backgrounds became visible, and instead of an array of blobs, only one single blob was shown on each side of the screen. The two blobs in the left and right patterns were separated by 10.4 deg, corresponding to the center distance of blob arrays in condition A. In a third *condition C*, referred to as *focal brightness match*, stimulus presentation was identical to condition B (single blobs, no hard-paper mask) but targets were now viewed and compared foveally, in alternation.

To enhance brightness effects (if present), blob size was increased to 1.1 deg by 1.1 deg (compared to 0.4 deg by 0.4 deg in Experiments 1 and 2). However, to confirm the findings in the context of the main study, condition A was also tested, in an additional test, in patterns with the original blob size.

Results and Discussion

As expected, the *lightness* and *brightness matches* with single targets (conditions B and C; Figs. 11 and 12) generated distinct curves for each triplet of reference patterns at same target-to-background contrast but

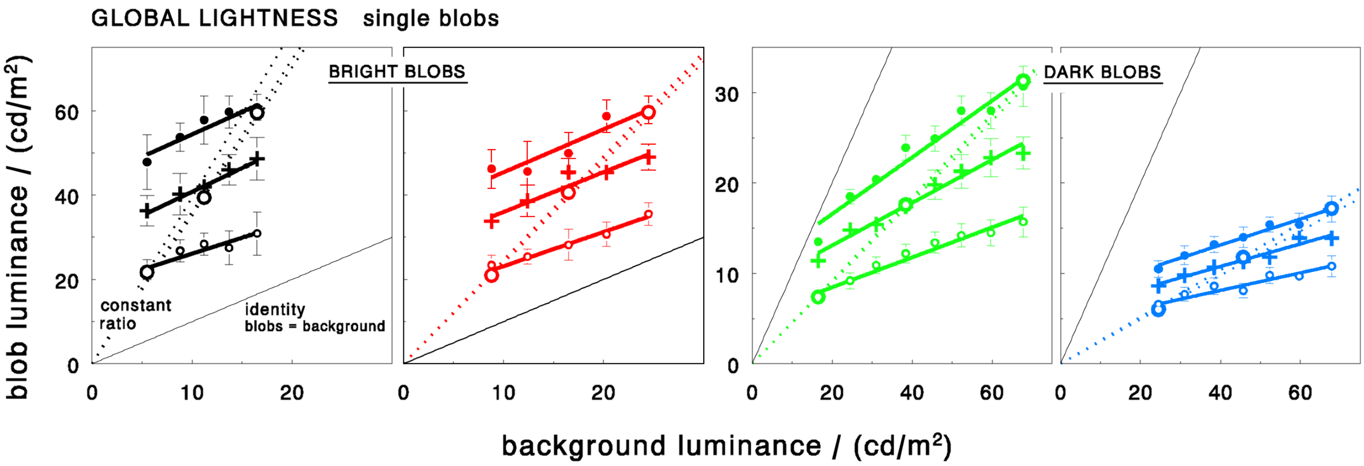

Figure 11. *Matches of Experiment 4, condition B.* Detailed exploration of four test series (different colors) from Experiments 1 and 2, which had shown notable deviations from the constant-ratio principle. Unlike the original experiment, test series were repeated with different reference patterns (large open symbols), the luminance settings of which lied on the expected constant-ratio lines (dotted curves). Thick continuous lines are regression lines through the data; thin continuous lines represent target-background identity. If matches would follow the constant-ratio rule, all data points of a graph should fall upon the dotted lines and regression lines should fall upon another. When blobs were globally matched for lightness, as in the data shown here, curves strongly deviate from this prediction and matches with different reference patterns produce separated curves.

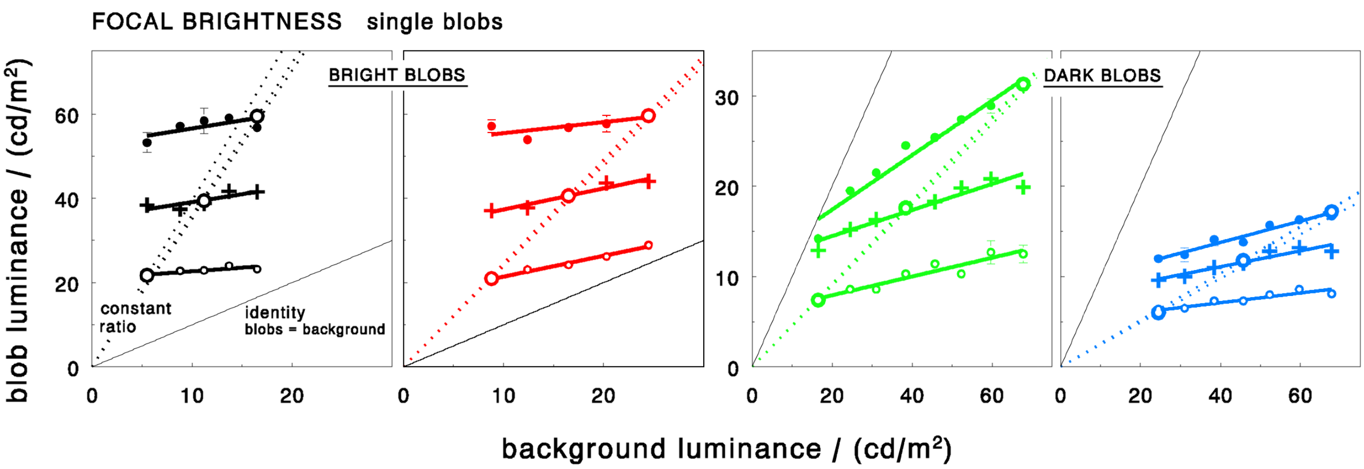

Figure 12. *Matches of Experiment 4, condition C.* Curves become almost flat, when blobs were foveally matched for brightness. Presentation as in Figure 11.

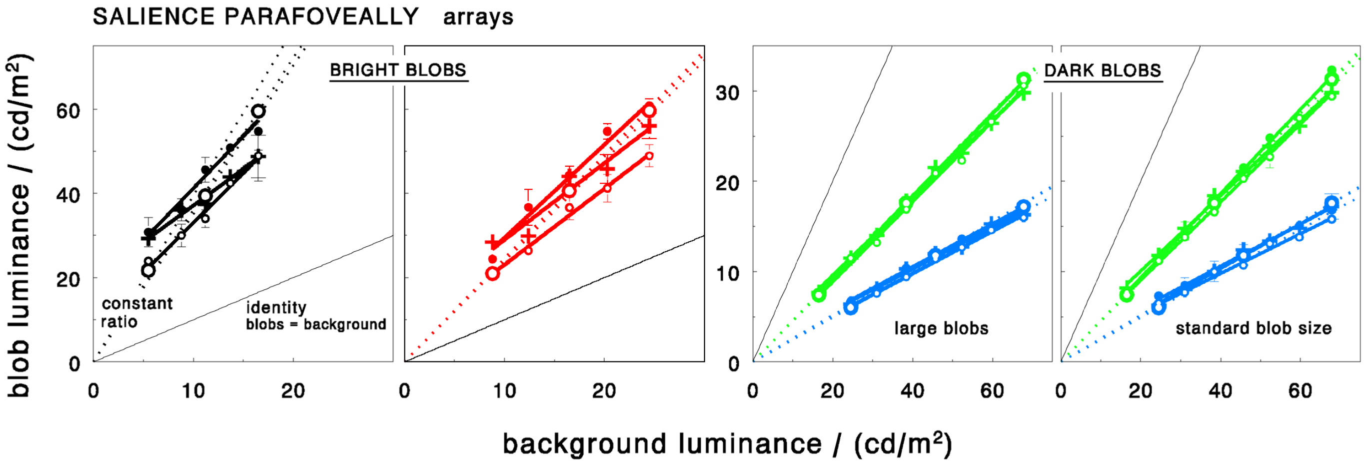

Figure 13. *Matches of Experiment 4, condition A.* When blob arrays were parafoveally matched for salience, data from different curves fall together and close to the constant-ratio predictions. This was particularly clear for dark blob matches, so that the data from two graphs could be plotted into one (third graph). The right-most graph shows data from the same experiment with the standard blob size from Experiments 1 and 2. Data presentation otherwise as in Figures 11 and 12.

different target luminance (large open circles). The slopes of all these curves were flatter than predicted from the constant-ratio rule (dotted lines). Focal brightness matches under foveal inspections (condition C; Fig. 12) produced even flatter curves than the global (parafoveal) lightness matches (condition B; Fig. 11). Note that curves should be strictly horizontal in the foveal brightness matches if background luminance could have been completely ignored.

By contrast, the peripheral *salience matches* in condition A produced quite different results (Fig. 13). The curves from different reference patterns at the same contrast were now more similar and all followed the constant-ratio slope. The curves for dark blobs even overlapped completely.

The experiment confirmed the assumption that the slope deviations from the constant-ratio rule might have been caused by various effects in lightness and brightness perception. If subjects had managed to ignore these effects, their salience matches might have been closer to the (constant-ratio) predictions..

In condition A of the present experiment, brightness effects were largely excluded by performing the match parafoveally and ensuring that mainly blob conspicuity was evaluated. This produced curves that closely followed the constant-ratio principle. When, on the contrary, matches were explicitly made for lightness or brightness, globally or focally, strong deviations from the constant-ratio principle were seen. They generally led to flatter curves than the salience matches, both for dark and bright blobs. Note however, that even the foveal brightness matches (condition C) did not produce totally flat curves what they should if brightness could have been matched independent of the surrounding backgrounds. This indicates that there were notable induction effects from simultaneous contrast and perhaps even assimilation.

Experiment 5: Blob arrays vs. single blobs

Lightness and brightness perceptions are strongly affected by stimulus context. It had turned out in preliminary experiments of this study that salience matches of blobs in different geometrical configurations could differ under certain circumstances. While such variations were negligible when both patterns displayed the same blob density, differences could be pronounced when blobs in a dense arrangement, on the one side of the screen, were compared with sparsely arranged or single blobs, on the other side of the screen. This suggested to run a complete experiment on this phenomenon and to match the salience of a constant single blob to that of blobs arrays in various spatial arrangements. Such comparisons should reflect contrast and assimilation effects if lightness or brightness would contribute to salience matches. I will present the data and analyze them for the spatial range of induction effects.

Method

Task and procedures were similar to Experiments 1 and 2, except that matches were performed with a test pattern that displayed only one single blob in the center, and with reference patterns at various blob densities. In seven test series, the geometrical configuration of blobs in the reference pattern was varied from dense to sparse arrangements. The settings were *dense* (9 x 17 raster; raster width, *rw,* of 0.5 deg), *less dense* (7 x 13; *rw*=0.7 deg), *middle* (5 x 9; *rw*=1.0 deg), *wide* (3 x 5; *rw*=2.1 deg; as in all other experiments of this study), *sparse* (1 x 3; *rw*=4.2 deg), *very sparse* (1 x 3; *rw*=5.8 deg), and *single* in which the reference pattern displayed only one single blob, as the test pattern. Note

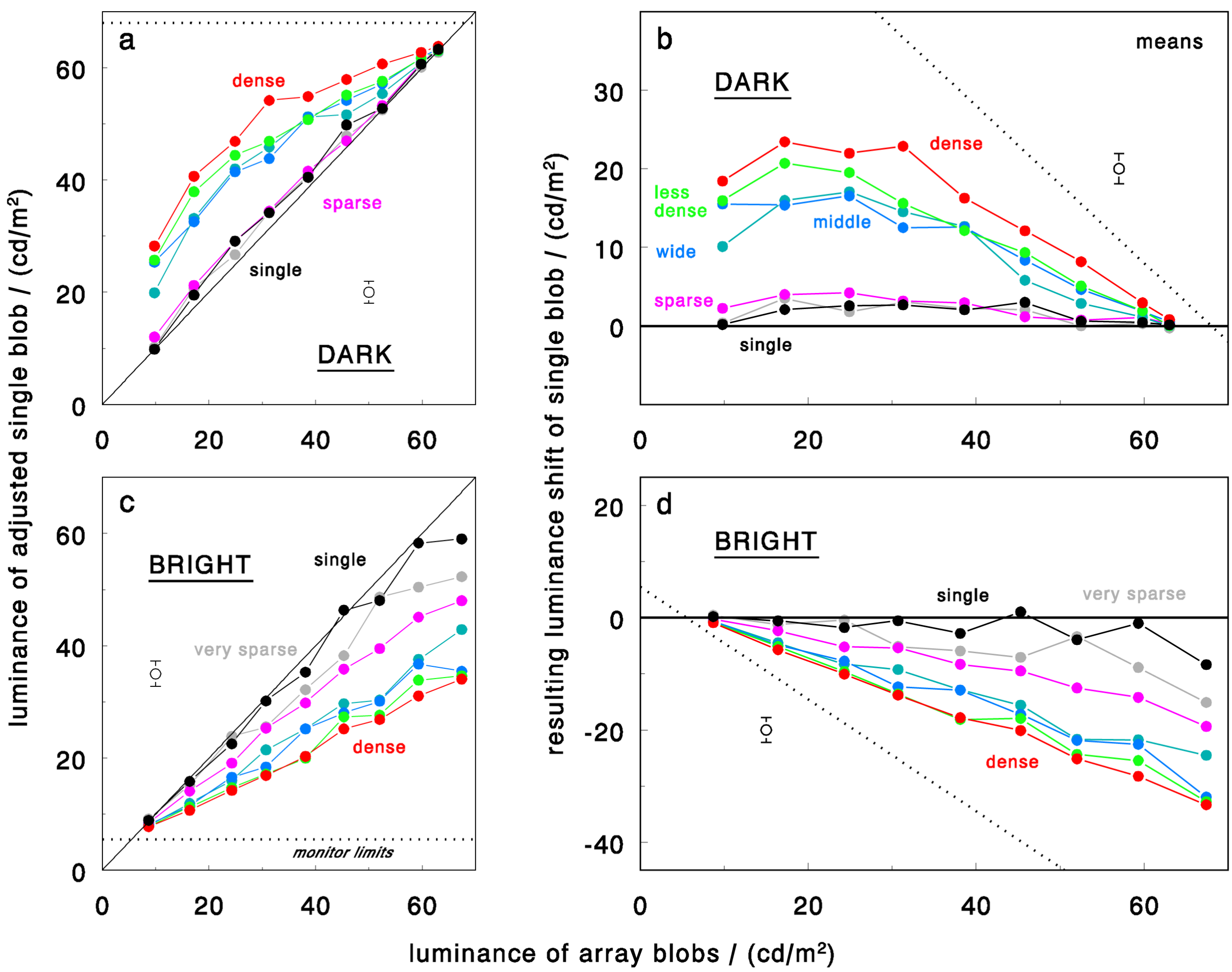

Figure 14. *Assimilation effects in salience matches (Experiment 5).* In different test series (data plotted in different colors), subjects matched a single test blob to various blob arrays in reference patterns so that all blobs appeared equally salient. Graphs plot the mean data of all three subjects; the averaged s.e.m. is shown separately (circles with error bars). **a, b.** Tests with dark blobs. Single blobs were regularly adjusted brighter than similarly salient blobs in dense arrays. **c, d.** Tests with bright blobs. Single blobs were adjusted darker than blobs in dense arrays. Graphs in **a** and **c** show blob luminance; graphs in **b** and **d** deviations from equal-luminance settings.

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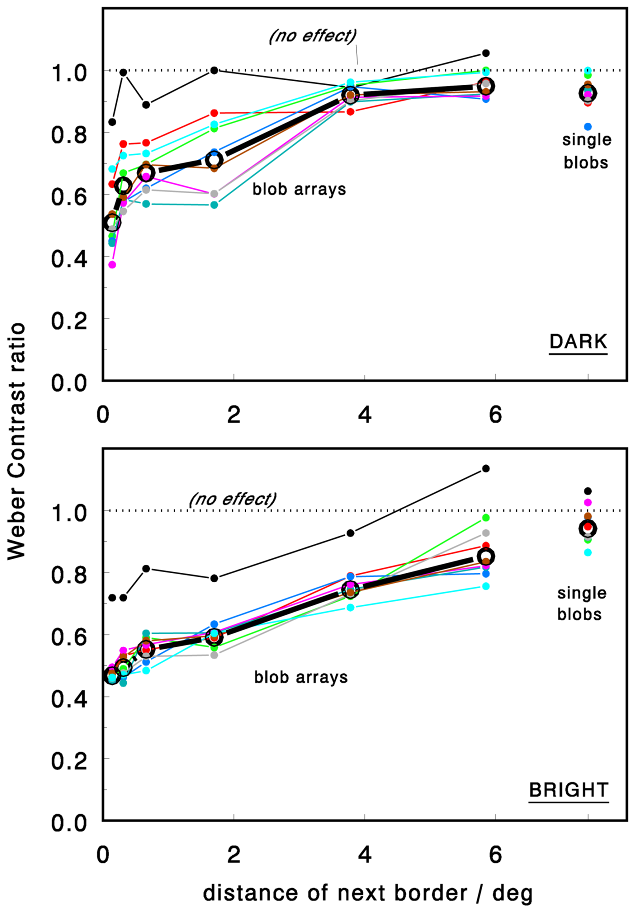

Figure 15. *Assimilation effects as function of the inter-blob distance.* The data of Figure 14 are re-plotted at the distance from the next (inducing) blob border; attenuation effects are given as the ratio of Weber contrasts of the adjusted single blob and the according blob array, which is equivalent to the ratio of matched and original increments or decrements (for details, see text). The color coding is not related to Figure 14. Each blob array is now represented by its inter-blob spacing, and data along each curve in Figure 14 are here re-plotted as different data points at this distance. Except for the lowest blob contrast tested (small black circles and thin black lines), for which no attenuation effect could be measured (right-most data points in Figure 14a, b; left-most data points in Figure 14c, d), assimilation effects in salience matches were similar over all tested contrast settings and diminish with increasing distance from the inducing border. Large black symbols and thick connection lines plot the averages of all curves except the black low-contrast curves.

that in *sparse* and *very sparse* arrangements, the blob raster was reduced to a single row of three elements. Within each test series, blob luminance was systematically varied. Reference and test patterns had always the same background luminance (68 cd/m^2, for dark blobs; 5.5 cd/m^2, for bright blobs). The subjects' task was to adjust the luminance of the single test blob until it looked equally conspicuous as the blobs in the reference raster; subjects were not asked to match the targets for lightness or brightness. Matches were performed with dark and bright blobs, so that the whole experiment included 14 test series (7 on dark blobs, 7 on bright blobs), each with 9 matches presented twice in a random order. All tests series were run one to two times by each subject.

Results and Discussion

Performance of the three subjects was qualitatively similar and data are pooled for presentation. The averaged matches are shown in Figure 14. In nearly all matches, the contrast of the single blob had to be attenuated to make it appear as salient as the blobs in the according raster display. That is, single dark blobs were adjusted brighter (Fig. 14a, b), and single bright blobs darker (Fig. 14c, d) than the same blobs presented in arrays. This effect was strong in dense and very dense arrangements and diminished towards sparser arrangements. It was nearly absent in the sparsest arrangements tested and (of course) in the matches of single blobs on both sides of the screen.

The attenuation effect was also modulated with target contrast. For dark blobs, deviations were nearly constant for luminance settings up to about 30 cd/m^2 and decreased when blob contrast to background was further diminished (Fig.14b, moving towards the right). For bright blobs, deviations continuously decreased with decreasing blob contrast to background (Fig.14d, moving towards the left). Figures 14a and c indicate that the gradual decrease of induction effects was not due to monitor limitations (dotted lines).

When looking at medium and dense blob arrays, blob and background colors seem to "assimilate"; densely arranged dark blobs on a bright background appear brighter, and bright blobs on a dark background darker, than an identical single blob on the same background, which looks also more salient than the blobs in the array. The apparent color shift is opposite to that of simultaneous contrast which should enhance but not attenuate the difference between targets and background (Blakeslee & McCourt, 2004). Note that a different interpretation might also be valid, as we are comparing two patterns without an objective reference. It could also be that the single dark test blob appears darker, from simultaneous contrast, and that this contrast is weakened when other blobs are presented nearby. In any case, the observed attenuation effect modulates brightness and apparently salience, too.

Assimilation effects are known to depend on the distance of the modulating border (Blakeslee & McCourt, 2013; Reid & Shapley, 1988). To analyze the influence from nearby borders in the target surround, the data of Figure 14 are re-plotted in Figure 15. Attenuation effects from different blob contrast are now superimposed and plotted against the distance to the nearest border of the surrounding blobs (small symbols, thin lines). Instead of luminance deviations from identity, data are now plotted as ratio of the Weber contrast, *WC,* of single blobs and blobs in the array,

$$\frac{WC_{single\ blob}}{WC_{blobs\ in\ array}} = \frac{|tg_{single} - bg_{single}|}{bg_{single}} \cdot \frac{bg_{array}}{|tg_{array} - bg_{array}|} \ ,$$

which simplifies to

$$WC\ ratio = \frac{|tg_{single} - bg|}{|tg_{array} - bg|}$$

for the identical backgrounds used .

Except for the very low contrast conditions (small black circles, thin black lines) data points from different curves (representing different target contrast) fall close together and do all show the dependence of attenuation effects from the distance of the inducing border, that has been reported for assimilation effects (Blakeslee & McCourt, 2013; Reid & Shapley, 1988).

Discussion of Section II

The results of Experiments 4 and 5 confirm the suspicion that the salience matches of blobs are affected by brightness effects that cannot always and easily be ignored. These effects were also seen in the salience matches of Experiments 1 and 2 and have likely produced the notable deviations from a simple constant-ratio rule. Only when the influence of lightness was minimized, like in condition A of Experiment 4, was salience closely related to the luminance ratio of blobs and background (Fig. 13) as given by the Weber or Michelson contrasts.

However, although the influence of brightness effects on salience matches varied between subjects (cf. Fig. 3, curves at label 1) and could even be modulated by the test paradigm, one must not interpret them as an artifact. They indeed do affect the salience of items, as is easily verified in Figure 10. The problem in finding the appropriate match is not the disturbance by brightness effects but the difficulty in deciding which salience aspect to match. Depending on what we consider most important, we may look at the global uniformity of blobs, their similar distinction from different backgrounds, or the equal brightness of individual blobs. While we would likely not rate blobs in the latter match (e.g., Fig. 10j) equally conspicuous, there might be gradual variations in intermediate matches (Fig. 10d-h). Matching dark and bright blobs either for brightness or apparent contrast will give quite different results (du Buf, 1992b). But whether contrast and brightness both contribute in an equal way to *all* functional properties of salience, is another and still open question. It seems unlikely that the first, salience-driven gaze shift to a new stimulus would be strongly affected by slow (and perhaps even cognitive) processes of brightness perception. Later salience estimates, however, and actions based on them, may reveal such effects. For the fast detection of a stimulus, previous salience effects (from orientation contrast) will only briefly affect reaction time (Donk & Soesman, 2010).

In the salience matches of the present study, observers looked at the patterns for considerable time while adjusting blob luminance. This might have strengthened the influence of brightness effects that might be less effective when salience must be quickly evaluated. I have evidence for that from grouping experiments in which the fast analysis of complex stimuli favored the salience from luminance contrast over target lightness or brightness (Nothdurft, 1995, and unpublished results). This is supported by Moore and Brown (2001) who have shown that observers have access only to "pre-constancy" information (information that is not yet corrected for, e.g., lightness constancy) in visual search. You can get a similar impression when looking at Figure 10 while blinking with your eyes; if inspection time is short, the selection of the best matching patterns seems to be little affected by target brightness and blob similarity so that the estimates of equal salience shift back to (c)-(e). Schirillo (1999a, b) has reported that even brightness and lightness matches themselves better followed the constant-ratio rule when targets were presented on an "articulated" background.

With lightness and brightness effects entering salience matches, we may run into a huge package of problems when trying to define a simple rule of salience computation, as is well documented in numerous studies on lightness perception and brightness matches. The perceived lightness is not only affected by the observer's evaluation of whether luminance patches are self-luminescent or presumably reflecting surfaces (Arend & Goldstein, 1987; Gilchrist, 1988; Robilotto & Zaidi, 2006; Schirillo 1999a, b). It is also influenced by the nearby luminance distribution in the scene (cf. Barkan, Spitzer, & Einav, 2008; Blakeslee & McCourt, 2004; Bressan & Kramer, 2008; Hong & Shevell, 2004; Reid & Shapley, 1988;) and even by the (cognitive) interpretation of a scene in terms of 3D shape and global shadows (Adelson, 1993; Logvinenko & Kane, 2004; Logvinenko & Ross, 2005; Perkins & Schirillo, 2003; Robilotto & Zaidi, 2006; ; for a recent review, see, e.g., Kingdom, 2011).

III. EQUAL-SALIENCY MATCHES OF TARGETS AT DIFFERENT CONTRAST POLARITIES

While Experiments 1 and 2 helped to understand and predict equal-salience settings of targets at equal lightness, we do not yet know how the salience of dark targets would relate to that of bright targets, and vice versa. This is studied in the following two experiments.

Experiment 6: Salience matches of bright and dark blobs on similar backgrounds

Dark blob arrays were compared with bright blob arrays on the same background luminance. Since blobs differed in luminance polarity and subjects could not match them for similar lightness or brightness, we should perhaps expect smaller or no interference at all from brightness variations than in the previous experiments.

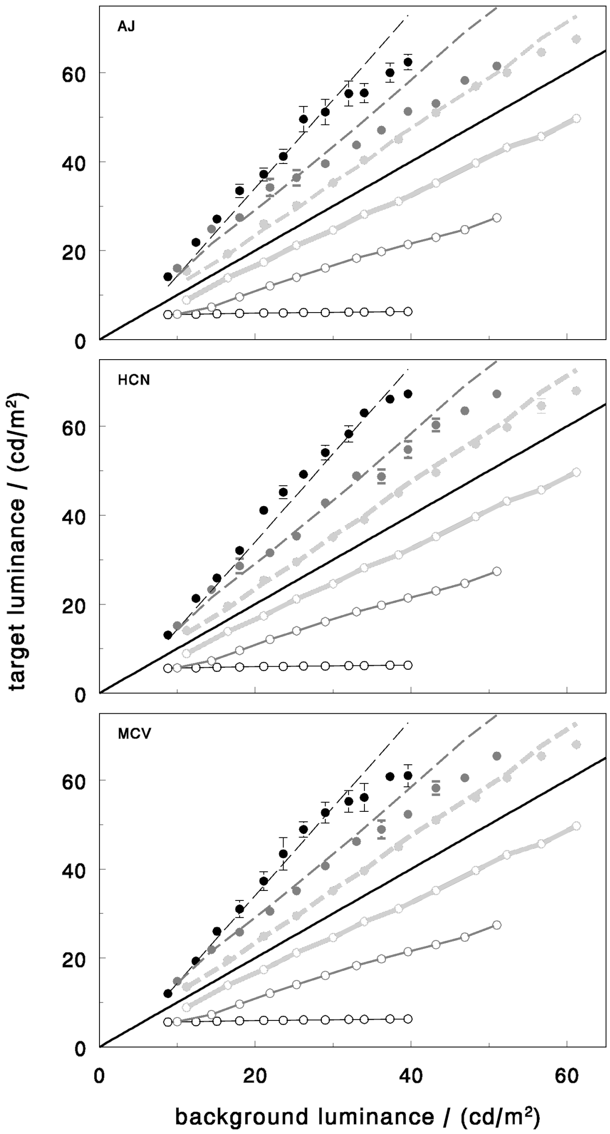

Figure 16. *Equal-salience matches of bright to dark blobs on identical background (Experiment 6).* Graphs show each subject's data to three test series (black, grey, light-grey). Different to previous figures lines do not represent equal salience but connect the various conditions of a test series; the corresponding luminance settings of reference patterns (open circles) and equal-salient test patterns (filled circles) are plotted at the same background luminance. Thick continuous lines across each graph mark zero contrast at blob-background identity. Dashed lines above show the predictions from constant Weber contrast (decrements = increments) for each series. The salience-matched bright blobs followed these predictions but tended to deviate at increased contrasts. Error bars show the s.e.m. of individual matches.

Method

Procedures were the same as in Experiments 1 and 2 except that dark or bright blobs were now compared with blobs of opposite contrast polarity. Only wide blob arrays with the same geometrical properties as the arrays in Experiments 1 and 2 were used. The experiment included five test series (six for subject HCN); in three of them bright blob arrays were matched to dark blob arrays, in the remaining two (three) series, dark blobs were matched to bright blobs. Different to the earlier experiments, reference patterns were not held constant in a test series but varied from one trial to the next. The backgrounds of the two patterns in a given display were always identical.

Results

The task was slightly more difficult than the previous matches but subjects quickly adapted to it and produced reliable salience matches with small s.e.m. The data are circles) fell close to these predictions but others clearly deviated from them, particularly when blob contrast was increased.

A number of additional tests (with arrays of larger blobs or with single blobs) were performed to search for an explanation of these deviations. All these tests generated qualitatively similar results (not shown here), and similar deviations from the predictions.

A possible cause for the deviations can be derived from Fig.17 which shows the mean data of all three subjects. The plot in Figure 17a is similar to Figure 16 (but axes are

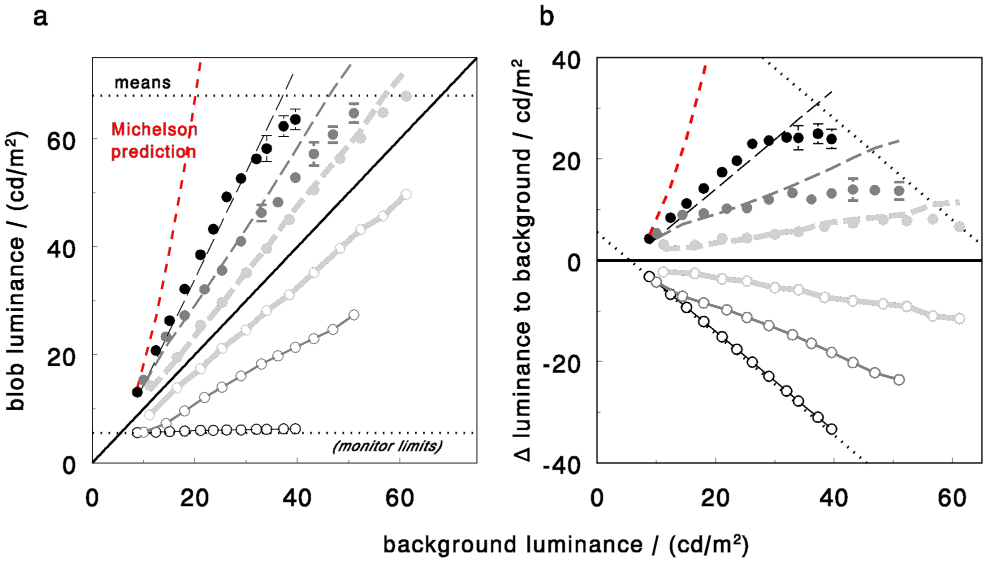

Figure 17. *Means (and s.e.m.) of the data in Figure 16.* **a.** Same (but compressed) presentation; **b.** re-plotted as increments and decrements from background. Predictions from constant Michelson contrast (dashed red line) are shown for the test series with the largest blob contrast (black). The symmetry of data above and below background is clearly seen in *b*, as are the deviations towards constant addition at larger contrasts. Data do not follow the predictions from constant Michelson contrast. Luminance restrictions of the monitor are marked by dotted lines.

shown in Figures 16-18. Data points from the same test series are connected and do now include tests conditions with different salience. Open circles represent the settings of reference patterns, filled circles (at the same background) the according settings of the salience-matched test patterns with blobs of opposite contrast polarity. Dashed lines indicate the luminance settings that would be expected if salience were defined by equal luminance differences of the dark and bright blobs to background (increment = decrement), as for example obtained with the Weber contrast. Many matches (filled now plotted at the same scale); these data are re-plotted in Fig.17b now showing the luminance difference between background and targets. Here, it is obvious that luminance differences settled at a certain level and did not further increase with further increasing contrast of the dark blobs. Thus, the salience representation of bright blobs appeared to saturate. Note however, that saturation levels were not identical for the three curves and were not related to monitor limitations (indicated by dotted lines).

The analogue salience matches of dark test to bright reference blob arrays are shown in Fig.18. Again, the

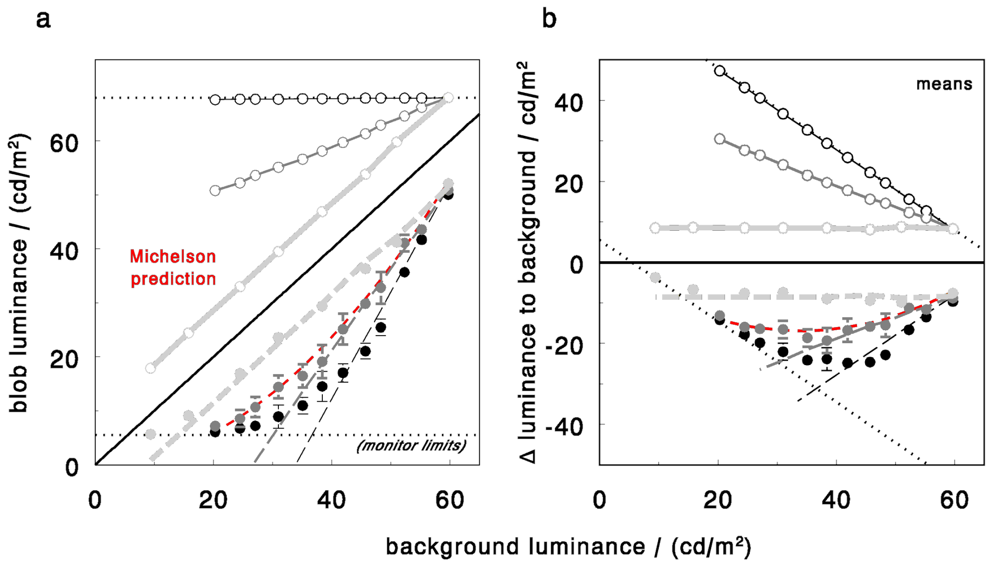

Figure 18. *Equal-salience matches of dark to bright blobs on the same backgrounds (Experiment 6).* Presentation as in Figure 17, except that reference patterns displayed bright blobs (open circles) and test patterns dark blobs (filled circles). **a.** Luminance settings of reference and salience-matched test blobs; **b.** same data plotted as luminance deviations from background. Mean data and s.e.m. of all subjects (except the data in light-grey, which were obtained only from HCN). Red dashed lines give the predictions from constant Michelson contrast for the test series with the strongest blob contrast (black). Similar to the reversed matches of bright to dark blobs in Figure 17, data follow the Weber but not the Michelson contrast and tend to deviate at larger blob contrast.

adjusted blob contrast followed the predictions from Weber contrast up to a certain level and then appeared to saturate. In these matches, however, further increases of (bright) blob contrast in the reference patterns had sometimes led to test matches that were affected by monitor limitations (dotted lines). But saturation was already seen before this limit was reached.

Discussion

While the salience matches of dark and bright targets closely followed the predictions from Weber contrast for small to medium blob contrast, they were generally smaller than predicted for large contrast settings. This finding is contrary to several studies which have shown that dark targets are more conspicuous or more effective than bright targets at the same Weber contrast (e.g., Bäuml, 2001; Dannemiller & Stephens, 2001; du Buf, 1992a; White, Irvin, & Williams, 1980; Zele, Cao, & Pokorny, 2007). Some studies obtained better matches of increments and decrements when using different contrast measures (Dannemiller & Stephens, 2001; Vassilev, Murzac, Zlatkova, & Anderson, 2009; Whittle, 1986). Dannemiller and Stephens (2001), for example, had noted a mismatch of dark and bright popout targets in children, which disappeared when they plotted the data against Michelson instead of Weber contrast. They stated, however, that they have not seen these differences with a Weber contrast of up to 52% (p. 121). While the grey curves in my data (Figs. 16 and 18) were below this limit, the black curves clearly exceeded it. Du Buf (1992b), on the other hand, though on a much brighter background, noticed a difference between brightness perception and apparent contrast. For an equal *brightness* difference to background, luminance increments were more effective than decrements (contrary to the other studies which reported a stronger effect from decrements); for an equal *apparent contrast*, both were about equally effective. This is more similar to the salience matches in the present study, where equal luminance increments and decrements were about equally salient. Only for the larger blob contrasts in a series, both increments and decrements showed saturation effects.

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It is obvious that these deviations cannot be explained by the usage of a perhaps inappropriate measure of target contrast. The Michelson contrast, for example, would compress the luminance variation of bright stimuli; hence luminance settings of Michelson-matched bright blobs should have been much larger than those predicted from Weber contrast (cf. the red curves in Figs.17 and 18), but not smaller, as observed in Experiment 6. The same argument would reject an explanation that deviations could be due to an improper scaling of luminance, by using linear instead of power differences (with an exponent $x<1$). Stevens' brightness law (1961), too, should have compressed the luminance scale for bright stimuli; that is, equal-salient bright blobs should have been adjusted even *brighter* than predicted from the Weber contrast. Instead, the data indicate that all three subjects, when matching bright to dark targets (or *vice versa*) approached a certain luminance difference between target and background that was not further exceeded when matching reference blobs with a larger contrast (Figs. 17b and 18b).

Experiment 7: Salience matches of bright and dark blobs on different backgrounds

The stimuli tested in Experiment 6 were special in that the dark and bright blobs were presented on identical backgrounds. To generalize the findings it seemed interesting to expand the matches to dark and bright blobs on different backgrounds. This was done in the following experiment, which was performed by a different group of subjects at a later stage of the project.

Method

Experiment 7 included five test series with altogether 44 test conditions. Two of these series presented dark and bright blobs on strongly different backgrounds (5.5 cd/m^2, for bright blobs; 68 cd/m^2, for dark blobs); the other three series were included to confirm the previous findings and showed dark and bright blobs on identical backgrounds, which however were constant within each series and differed between the three series (24.5 cd/m^2; 38.4 cd/m^2; and 52.3 cd/m^2). The matching procedure was identical to that used in the previous experiments. Two of the three previous subjects had been replaced for these tests.

Results and Discussion

The matches from all test series are shown in Figure 19a; the three subjects performed similarly and data were averaged. The different test conditions are plotted separately in Figures 19b and c. The two curves from the test series with *different* backgrounds look quite similar (black symbols); in one series, bright test blobs were matched to dark reference blobs (open circles), in the other series, dark test blobs were matched to bright reference blobs (filled circles). Thus, data points from different curves even when falling close together represent (similar) blob luminance on different backgrounds. Different contrast effects may then explain why the curves are not exactly identical. To extract from these curves all matches of blobs on one particular background it is necessary to recombine the data and partly exchange reference and test pattern settings, as is shown in the grey curves in Figure 19b. Data from the remaining three test series with dark and bright blobs on *identical* backgrounds are plotted in different colors (Fig. 19c).

The main findings from this figure are very clear. Matches of dark and bright targets on same backgrounds fall on straight lines that run perpendicular to the identity line. Matches of dark and bright lines on different backgrounds show a qualitatively different, hyperbola shaped course.

These curves are compared with predictions from three distinct algorithms in Figure 19d-f. No single algorithm alone can predict the data from all test series. While the straight lines in Figure 19c are consistent with a salience computation based on the Weber contrast (cf. the colored curves in Fig. 19d) but not with salience computations based on the Michelson contrast (Fig. 19e) or constant differences of luminance power (Fig. 19f), only the latter computation could qualitatively predict the salience matches obtained with blobs on different backgrounds (cf. the black curves in Fig. 19b and f). To fit the predictions from constant Michelson contrast (Fig. 19e), the data curves should have been bent more strongly. Predictions thus confirm the findings of Experiment 6 that salience matches of dark and bright blobs on the same backgrounds follow the Weber contrast. By contrast, the hyperbola-shaped curves for blobs on different backgrounds would be consistent with a salience computation based on power-transformed luminance differences as described by Stevens' brightness law (Fig. 19b). This was further verified in computational fits to the data. The data in

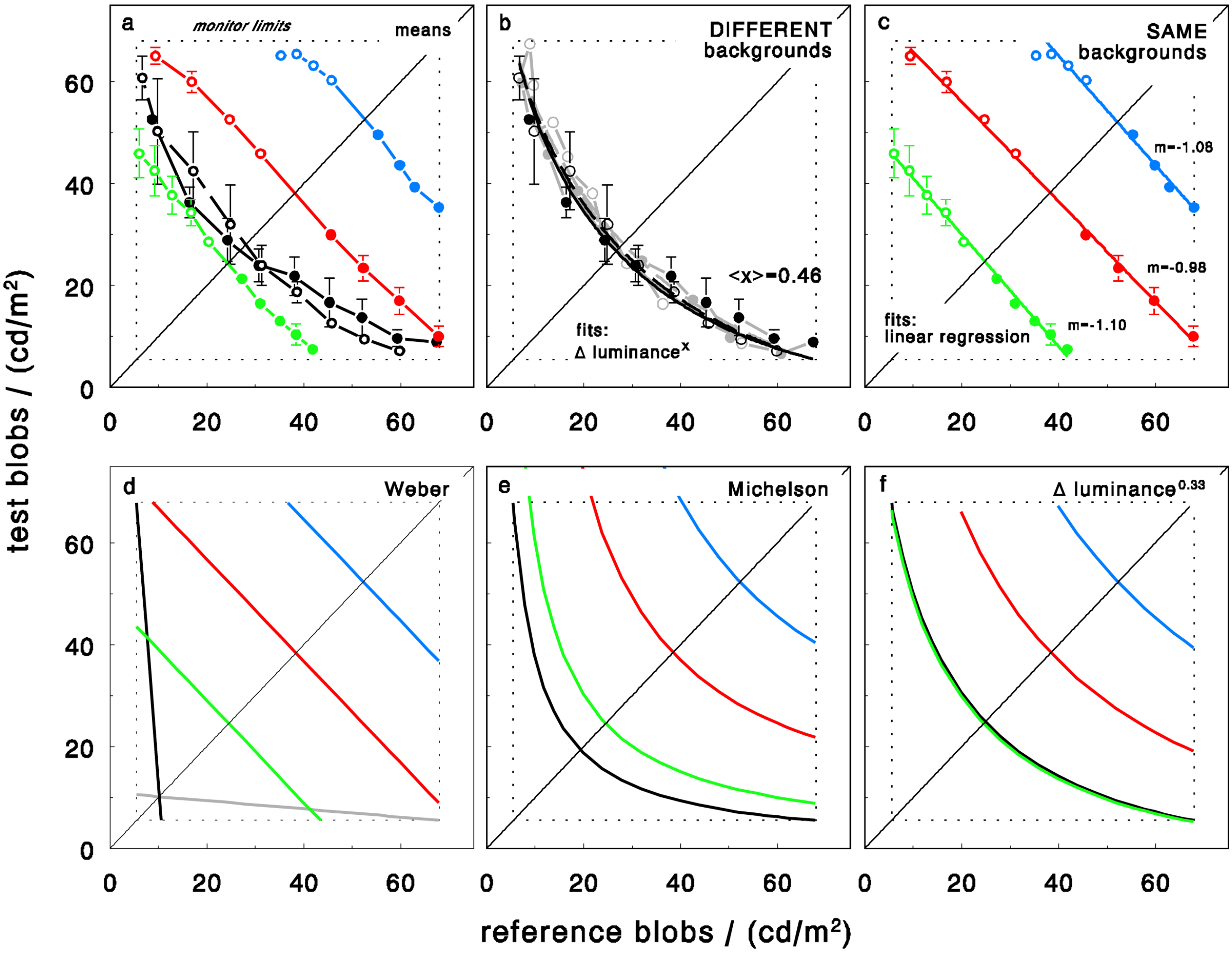

Figure 19. *Equal-salience matches of dark and bright blobs in Experiment 7.* **a–c.** Experimental data; matches of blobs on different backgrounds are plotted in black and grey, matches of blobs on the same backgrounds in color. Test series included matches in both directions; filled circles are from test conditions in which the dark blob array in the test pattern was matched to the bright blobs of a given reference pattern, open circles represent data from matches of bright test blobs to dark reference blobs. The raw data in **a** are split for different background conditions (**b, c**) and curves are fitted by power functions (*b*) and linear regression lines (*c*); see text for details. **d–f.** Computational predictions of matching performance in *a-c* when equal salience were obtained from constant Weber contrast *(d)*, constant Michelson contrast *(e)*, or constant differences in the power of luminance *(f);* color coding as in a-c. None of these predictions can simultaneously explain the data for same and different backgrounds. Equal-salience matches of blob arrays on the same background are well predicted by the Weber contrast (*d*); matches of blob arrays on different backgrounds by Steven's brightness law (constant Δ luminance $^{0.33}$; *f*). Oblique lines indicate the identity of reference and test blob luminance; intersections with colored data curves give the constant background luminance in the according test series. Faintly dotted lines show the luminance limits of the monitor.

Figure 19b were fitted by power functions with an unknown exponent x; best fits were obtained for exponents $0.43<x\leq0.51$ with an average of $x=0.46$. The data in Figure 19c were fitted by linear regression lines; the resulting slopes were close to $m = -1.0$. While the exponent of the power functions in Figure 19b is slightly above the value reported for brightness perception ($x=0.33$; Stevens, 1961), the general course of data points is very similar.

It is thus important to note that the simple equal-salience prediction from Weber contrast (increment = decrement), which has been found in Experiment 7, does only hold for the special case of equal background luminance settings.

General Discussion of sections I - III

In seven experiments, I have attempted to measure and predict the salience of luminance differences in simple geometrical patterns. By and large, equal-salience matches of either dark or bright blob arrays on various backgrounds followed the constant-ratio rule, that is, blobs were equal salient when their luminance ratio to background was constant. Deviations were seen with particularly bright blobs, which could follow the constant-addition rule instead; blobs then appeared as equally salient if their luminance difference to background was constant. In all these patterns, the constant-ratio rule is predicted from both Weber and Michelson contrast. Direct matches of dark and bright blobs, which could distinguish between these measures, were mostly consistent with the Weber but not the Michelson contrast. Exceptions were seen for large luminance differences between blobs and backgrounds (Exp. 6), which revealed salience saturation effects, and for blobs presented on largely different backgrounds (Exp. 7) where salience matches followed Stevens' brightness law, though with a slightly larger exponent.

Within certain limits we may therefore state that blobs are similarly salient when their luminance ratio to the surrounding background is constant. This is ecologically useful as it would make salience of reflecting surfaces independent from changes in illumination. But as I will point out in the following discussion, even deviations from this rule, in particular the deviations observed here, may be ecologically useful.

Ecological luminance variations of targets

There are, in principle, two causes why target and background luminance in an otherwise constant scene would change; targets or backgrounds may change their luminosity, or they may reflect less or more light from their surfaces when scene illumination varies. Much of our visual environment is made of surfaces that are not self-luminescent, and one should expect that biological systems are well-adapted to treat and analyze this world of surfaces in a behaviorally appropriate way. Variations in illumination are very common, since sun and moon light is permanently modulated by shadows, clouds, and fog in the air. Thus, even when objects and backgrounds are constant and do not change their surfaces, their luminance would permanently change, and it should be helpful for the visual system to ignore these changes if they are not behaviorally relevant. Luminance modulations from illumination changes are purely factorial and follow the *constant-ratio rule*.

Self-luminescent targets, on the other hand, are less frequent in daily life, but frequency has increased due to artificial light sources and, more recently, TV and computer monitors. Light from self-luminescent targets would *add* to the reflected light. Thus, if the visual system would like to keep the conspicuity of a self-luminescent target constant over various illumination changes, it should compute salience according to the *constant-addition rule*. Such a situation is, for example, obtained if light bulbs, LEDs, or blobs on a monitor are illuminated by external light. There would be no difference in reflectance between different regions on the monitor, and illumination changes would similarly increase, or decrease the luminance in all regions of the screen. If not illuminated at all, a purely reflective target should display zero luminance, whereas a self-luminescent target would still display the luminance it produces.

It is *a priori* not obvious which rule a behaviorally well-adapted visual system should apply. That might depend on a general (and even cognitive) interpretation of the inspected scene. Indeed, there are numerous reports that subjects estimated lightness and brightness quite differently depending on the scenario (Adelson, 1973; Arend & Goldstein, 1987; Gilchrist, 1988; Logvinenko & Ross, 2005; Robilotto & Zaidi, 2006; Schirillo, 1999a, b). If patches displayed the structure and reflectance of a surface, or appeared at a different depth from the surround, the matches closely followed the constant-ratio rule. But if the reflexive property of a patch was less obvious, matches had sometimes shifted away in the direction of the constant-addition rule (Arend & Goldstein, 1987; Gilchrist, 1988; Schirillo, 1999a, b).

It seems reasonable to assume that the interpretation of items as self-luminescent objects would be particularly adequate for very bright blobs. Indeed, matches that tended to follow the constant-addition rather than the constant-ratio rule were seen when the blobs to be adjusted were the brightest items in the scene (Exp. 2, Fig. 5). If the setup was reversed so that instead the reference blobs became the brightest items in the pattern and the test blobs to be adjusted were dimmer than these, the interpretation was changed and matches reliably followed the constant-ratio scheme (Fig. 4). The difference between equal-salience curves following the constant-ratio principle and equal-salience curves following the constant-addition rule is sketched in Figure 20a. As a matter of fact, subject HCN when performing additional test series on bright blobs to explore the cause of deviations from the constant-ratio rule (Exp. 4) also obtained matches that lay perfectly in the middle between constant-ratio and constant-addition predictions (Fig. 20b). This suggests that the different interpretations may coexist and that each of them may similarly contribute to the (mean) estimate of equal-salience matches. The long inspection time during the matches might have facilitated the averaging of different salience measures.

Asymmetries of bright and dark targets in Weber contrast

There is a general peculiarity with the computation of Weber contrast. While the values for dark blobs vary between 0 (*tg = bg;* no salience) and 1 (*bg = 0;* maximal salience), the values for bright blobs may raise to infinity when background luminance is low. Weber contrast has been a useful measure of target visibility near threshold (the brighter the background, the larger a luminance increment or decrement must be to become visible), and there is *a priori* no reason why this measure should not also be useful for salience comparisons above threshold. The present data, in fact, underline the (piecewise) validity of Weber contrast in salience estimates (cf. Exp. 6). In general terms, however, this cannot be the case, as the Weber contrast of a bright target on dark background may easily become a multifold of the Weber contrast of a dark target on bright background. How would the visual system deal with such an "asymmetry" between dark and bright stimuli?

One way to solve this problem would be to search for other contrast measures that may provide a more uniform representation of stimulus contrast across dark and bright stimuli. An obvious candidate is the Michelson contrast, which never exceeds 1. However, the salience matches of dark and bright blobs in the present study did not follow predictions from the Michelson contrast (but did follow

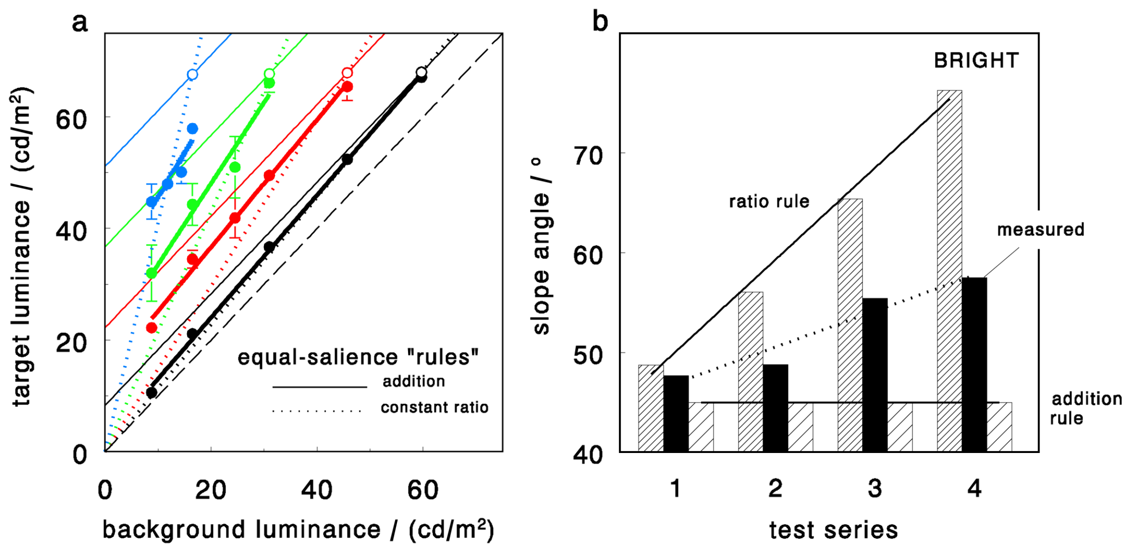

Figure 20. *Constant-ratio and constant-addition predictions in the presentation scheme of Figure 4.* **a.** Data from a repetition of four test series of Experiment 2 by HCN to find out about deviations from the constant-ratio rule. For constant ratio, salience matches should fall upon the dotted lines between reference patterns (open circles) and the origin. For constant addition, matches should fall upon the continuous lines parallel to target-background identity (dashed, black). The true matches (filled circles, thick regression lines) were found in between these curves. **b.** Slope angles of the curves in *a*. Constant addition would predict a slope angle of 45° for all test series (hatched bars). Constant ratio would predict slope angles increasing from slightly above 45° to much steeper angles, for the different test series (densely hatched bars). The obtained matches (filled bars) fell in the middle between these predictions suggesting an almost perfect averaging of the different salience effects in these tests.

the predictions from Weber contrast; cf. Figs. 16-19). Another way to avoid the computational asymmetry of the Weber contrast would be to use power-transforms of luminance, as in Stevens' brightness law. This is supported by the data of Experiment 7, where the salience of dark and bright blobs on different backgrounds was compared. However, Stevens' brightness law did neither reliably predict the salience matches of dark and bright targets on identical backgrounds (Fig. 19) nor those of dark blobs on different backgrounds (cf. Fig. 4b). This apparent validity of different rules made the exact computation of luminance-defined salience more complicated than originally expected.

Salience

The asymmetry of Weber contrast computations for bright and dark stimuli would also affect the according measure of salience. We have already seen in Experiments 1 and 2 that the strength of salience is qualitatively related to the luminance ratio of targets to background (represented by the different slopes of regression lines in Fig. 4). Curves near the oblique midline, with slopes of $m \approx 1$, indicate no or very little blob salience; for steeper or flatter curves, blob salience increases.

We also know from Experiments 6 and 7 how the salience of dark and bright targets on the same background is related. If luminance differences are not too large, targets with the same Weber contrast should be equally salient.

$$\frac{bg - tg_{dark}}{bg} = \frac{tg_{bright} - bg}{bg} \quad .$$

With the slopes in Figure 4,

$$1 - \frac{tg_{dark}}{bg} = 1 - m_{dark} \quad \text{(for dark items), and}$$

$$\frac{tg_{bright}}{bg} - 1 = m_{bright} - 1 \quad \text{(for bright items),}$$

this will simplify to

$$1 - m_{dark} = m_{bright} - 1 \quad .$$

Thus, the curves of equal-salient bright and dark blobs on the same background should lie symmetrical above and below the diagonal in Figure 4.

For dark targets, maximal salience would be obtained for absolutely dark targets at the slope $m=0$. The corresponding curve for bright targets would have a slope of $m=2$. But obviously, much larger luminance ratios, and steeper slopes can be obtained for bright targets and have, in fact, been tested in Experiment 2 (Fig. 4).

What would that mean for the salience matches of bright and dark targets? Formally, very bright targets on a dark background (with $tg_{bright}/bg > 2$) should fail to find an equal-salient dark target on the same background, since the quotient tg_{dark}/bg for the dark targets cannot be negative (at least not without additional, e.g. neural, mechanisms that would create a “super-contrast”). In praxis, however, there may be solutions around this formal rule. One solution could be that the salience from luminance contrast saturates so that the computationally very large Weber contrast of a bright target would not be more salient than the largest achieved (but computationally smaller) Weber contrast of a dark target. Indeed, Experiment 6 has revealed similar contrast variations for equal-salient dark and bright blobs up to a certain contrast level; further increases of the reference target contrast did not lead to further increments of test target contrast for equal-salient blobs. It is not clear, however, why this saturation was seen at different luminance levels in the three curves, dependent on the mean variation in a test series. A partly equivalent solution would be if the salience computation of very bright targets would switch to a different rule that produces less strong luminance increases. Such a rule would, for example, be the constant-addition principle, for which evidence was also found in the present study (cf. Figs. 5 and 17). A third solution, finally, could be that, under certain conditions, the salience encoding of both bright and dark targets would switch to a different scale and would, for example, relate salience to equal increments and decrements on the power of luminance. This was observed in Experiment 7 (cf. Fig.19b) and further evidence for this solution will be seen in Experiment 8.

Caveats

The role of attention. It would not be serious to end this major discussion without having stressed some general problems of salience matches in the present study. It has been shown (Carrasco, Ling, & Read, 2004) that the percept of luminance is notably affected by the focus of attention (see also Reynolds & Desimone, 2003; Treue, 2004). Attended targets may appear 5-12% brighter than non-attended targets (Carrasco, Ling, & Read, 2004). Since, for the salience matches in the present study, attention was alternately paid to both patterns, attention effects would unlikely have disturbed the measurements. But one has to be aware that equal-salient targets are only equally salient when they are either both attended or both non-attended, in particular when brightness effects interfere.

Automatic salience effects. There has been a long dispute about perceptual effects that are, or are not, *automatically* produced by salience (e.g., Bacon & Egeth, 1994; Belopolsky, & Theeuwes, 2010; Theeuwes, 1994, 2010; Yantis & Egeth, 1999; Yantis & Jonides, 1990; see also Awh, Belopolsky, & Theeuwes, 2012). It appears that in order to take advantages from certain salience effects, the visual system must be in a mode that would not mask or hinder the taking of such advantages. While certain salience keys, like the sudden onset of a stimulus, have earlier been argued to be more effective than others in attracting attention even when the system is perhaps not set into such a mode, it has now become more evident that salience effects can only work if the visual system is generally set to be ready for them (Belopolsky & Theeuwes, 2010; Theeuwes, 2010). This dispute is not touched in the present study where observers were explicitly instructed to look out for salience effects and compare them in strength. It may well be that all salience effects investigated here would be less obvious and perhaps even ineffective when observers block them under top-down control. If salience perception is not blocked, however, modulation of effects from luminance are graduated and different salience conditions can be compared, as was investigated here.

The role of salience from luminance in vision. The role of luminance contrast for salience in “normal” vision has been questioned (Einhäuser and König, 2003). The authors have analyzed the distribution of fixation locations when subjects inspected natural scenes. They found that, although observers sometimes looked at locations with increased luminance contrast, the *sequence* of gaze fixations could not generally be predicted from that cue. But this finding is perhaps less conclusive than suggested by the authors, and their interpretation has been questioned in later studies (Borji, Sihite, & Itti, 2013; Parkhurst & Niebur, 2004). Eye movements in (non-random) patterns resemble a highly complex process that would be based on various perceptual effects and would also be strongly influenced by a continuous (and even cognitive) interpretation of the inspected stimulus. Thus, the observation that sequences of eye movements do not reflect an automatism based on a low-level analysis (such as luminance contrast) alone does not reject the presence of graded salience effects from luminance contrast and the need to measure them. When perceived salience of regions in a scene is compared with the *first* gaze shifts after presentation of this scene, a high correlation of both measures is found (Borji, Sihite, & Itti, 2013).

Intermediate Conclusions

We can now resume three major problems from this discussion. First, the visual system is not only exposed to scenes in which target and background luminance would change according to a constant-ratio principle because of variations in illumination. Luminance variation may also follow a constant-addition rule, in particular when targets are brighter than the background and are presumably self-luminescent. Second, matches of bright targets can be difficult when adjustments have to be made to the highest luminance level of a scene. Matches are generally easier and more reliable when dimmer stimuli are to be adjusted (even if these are bright targets, hence brighter than their immediate surround). Third, there is an asymmetry problem with the computation of Weber contrast, which may, however, be solved by the saturation of salience effects with very large target contrast or by different scaling of luminance differences for bright and dark targets. Beyond these particular problems, however, salience is closely related to the Weber contrast of targets and backgrounds, both for dark and bright blobs, and targets with the same Weber contrast appear equally salient.

In the following section I will proof these conclusions in an additional experiment. In Experiment 8 the comparison of blob patterns was extended to a much larger luminance range than tested before to see if best matches are still obtained from constant-ratio settings.

IV. CONFIRMATION OF EQUAL-SALIENCE PREDICTIONS

The goal of this section was to generalize the previous findings and to confirm, or reject the presumed algorithms

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for equal-salience computations in a much wider luminance range than tested so far.

Experiment 8: Comparing predefined blob patterns

For that, a large number of reference patterns was created and completed with presumably equal-salient test patterns on the basis of previously discussed computation rules. The experiment was run in two versions. In version I, patterns were generated for the luminance settings of the previous tests now using the entire available luminance range (5.5-68 cd/m^2). In version II, a new LCD monitor with a much larger luminance range (0.1-220 cd/m^2) was used and patterns were generated to cover this available range. Observers were asked to evaluate the quality of matches and decide if blobs in the two patterns were similarly salient or blobs in one pattern were more salient than the blobs in the other pattern.

Methods and Stimuli

The tests on different monitors (internally referred to as "standard screen" and "flat screen") were performed in different sessions. Each experiment included three test series, for matches of dark, bright, and bright vs. dark blobs, respectively. Since subjects were asked for quick (and qualified) decisions instead of the time-consuming adjustments of blob luminance as in the experiments before, the number of test conditions and stimulus presentations could be increased, and each test series now included between 150 and 400 different test conditions.

Stimuli. Luminance settings of both monitors were carefully and repeatedly accessed. For pattern generation, luminance settings of the free parameters (background and blob luminance in the reference pattern plus background luminance in the test pattern) were systematically varied within the available monitor ranges, and then selected for the required target type (dark or bright). Luminance settings of the test blobs were computed from various algorithms; constant ratio ("ratio"; *tg/bg* constant), constant differences normalized to the maximum ("max"; *|tg-bg|/max(tg,bg)* constant), and constant differences in power transforms ("add"; $|tg^x\text{-}bg^x|$ constant) with one of five exponents (x = 0.33; 0.5; 0.71; 0.85; 1.0), the latter one representing the linear case (*|tg-bg|* constant). Conditions for which the predictions fell outside the available monitor ranges were ignored. Computations were made for each monitor. To concentrate measurements on the most interesting distinctions between algorithms, the collection of test conditions was reduced to only those conditions for which the various predictions of test blob luminance differed notably in at least one algorithm. The selection criteria were adjusted so that 30-70 test conditions for each tested algorithm remained; this was typically achieved by selecting test conditions with an at least 16 steps luminance difference between any two predictions; the differences between the other predictions might have been smaller. The resulting test series from different algorithms were finally combined, so that subjects saw a (long) test series with a random sequence of all selected predictions. Their responses, however, were linked to the individual algorithms used to generate the patterns and were accumulated over different test conditions based on the same algorithm.

Procedure. Subjects inspected the patterns in the same way as in the previous experiments, i.e. at a viewing distance of 75 cm and through a hard-paper mask in front of the screen. They were allowed, and actually encouraged, to look back and forth between the patterns to make a fair decision. There were three keys (on a computer keyboard) for an answer: "s" ("same") for "about" equal-salient blobs (subjects were not asked to search for differences); and "a" or "d" (keys to the left and right from the "s") if the blobs in the left- or right-hand pattern were notably more salient. There was no time pressure, but subjects were encouraged to make spontaneous (but qualified) decisions and not develop sophisticated rules like, e.g., evaluating differences in perceived brightness or explicit item contrast to the background. Subjects could not adjust target luminance. About 1s after the response was entered, a new pair of stimulus patterns occurred.

Subjects. The experiment was designed at the end of the project, when two of the subjects who had performed the majority of matching experiments in sections I-III were not further available. Thus, tests were performed by the remaining third subject (HCN) who had also run the previous equal-salience matching experiments, and the two new subjects who had already performed in Experiment 7.

Analysis. Data analysis was performed in two ways. (1) In a direct analysis, all *hits* (pairs rated as equally salient) for a given computational algorithm were accumulated and calculated in percent of all test patterns in this category. The ratings were averaged across subjects. Ideally, if salience were strictly based on a tested algorithm, ratings in this category should be near 100%. The opposite result, a rating of 0% percent in other categories, is not to be expected, as each category may include cases that would simultaneously serve also other algorithms. (2) In a more detailed computational analysis, all ratings for a given pair of blob patterns were accumulated and test conditions were later analyzed as to which algorithm they did represent. A test condition was included in the analysis of a certain algorithm if blob salience in the two patterns based on this algorithm did not differ by more than 5%. Ratings of all such pairs were then accumulated. This procedure also allowed for the analysis of complementary cases, i.e. of all test conditions that clearly did *not* follow that algorithm. In this "not algorithm" group were all test conditions included for which the blob salience in the two patterns differed by more than 20%. Test conditions with salience differences between 5% and 20% were ignored in the analysis of this particular algorithm. There were two reasons for using this procedure. One was that luminance predictions for the stimuli were not always exact but were restricted to the resolution of the luminance scales in experiment; deviations were notable in some cases. The other reason was that different algorithms might have generated similar predictions; ratings for different algorithms could then be misleading if these cases were only counted with the algorithms from which this pattern was created.

Results

The direct analysis of ratings, averaged over subjects, is shown in Figure 21. The percentages of "accepted" stimulus pairs (pairs rated as about equally salient) show systematic variations with the algorithms underlying the predictions; these variations are largely reproduced in the different luminance settings of both monitors (Fig. 21a and b).

For *dark blob matches*, predictions from constant ratio ("ratio"; Weber contrast) were rated best; subjects accepted most pairs of blob patterns generated with this algorithm as equally salient. But note that they have not accepted *all* stimulus pairs from this algorithm but did, on average, reject 25% as being not equally salient (the value varied between 10% and 45% across subjects). For dark and for bright blob matches, predictions from the "max" algorithm (luminance difference divided by maximum luminance) are computationally identical with those from the "ratio" group and not shown. Predictions from all other algorithms were rated worse. The modulation was obvious for patterns in the standard luminance range (Fig. 21a, "Standard screen") and even stronger for patterns with larger luminance variations (Fig. 21b, "Flatscreen").

The picture looks different for the *bright blob matches*. Predictions from the constant-ratio rule were only rarely rated as acceptable salience matches; much better ratings were obtained for predictions from constant addition, in particular when based on power-transforms of luminance. In the smaller luminance range of the standard monitor (also used in the previous experiments), best ratings were obtained for exponents of $x=0.5$ and $x=0.71$ (Fig. 21a) but maxima shifted to $x=0.33$ and $x=0.5$ with the larger luminance range of the "Flatscreen" (Fig. 21b). Note that the absolute ratings were then quite different across subjects (large s.e.m.) but relative ratings were similar.

For *matches of blobs at different luminance polarities* (Bright:Dark matches), ratings in the standard luminance range (with one exception) were only little modulated across algorithms (Fig. 21a). All tested algorithms had produced several stimulus pairs that were rated as equal-salient, and a similar number of stimulus pairs that were rejected; constant-ratio predictions received a slightly higher rating than the other algorithms. An almost perfect rating with 93%, however, was obtained for a subgroup ("bg=bg") of constant-ratio patterns in which bright and dark blobs were presented on the same backgrounds. Patterns with this restriction have revealed equal luminance differences between blobs and backgrounds (increment = decrement) and should thus be computationally identical with predictions from constant addition. But neither algorithm could generally predict equal salience when backgrounds were *not* identical. With the larger luminance range of the Flatscreen (Fig. 21b), however, differences between algorithms were more pronounced, and the subgroup of blobs on identical backgrounds did not receive so high ratings. Constant-ratio predictions then received only the second-best rating; the best rating was achieved for constant-addition predictions in the power-transform of luminance ("add

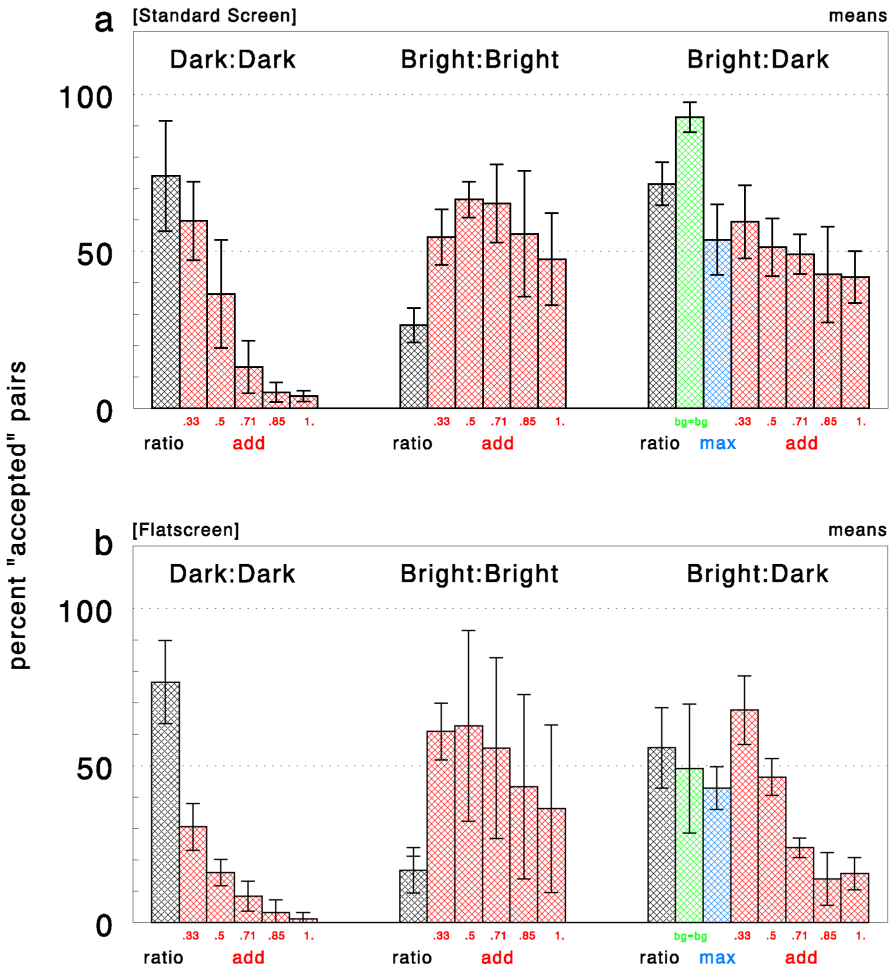

Figure 21. *Equal-salience ratings in the Confirmation Task (Experiment 8).* **a, b.** Data from different runs on two monitors with largely different luminance settings. "Standard Screen" *(a)* refers to the monitor and the luminance range used in all previous experiments (5.5-68 cd/m^2). "Flatscreen" *(b)* refers to a second monitor, tested only in Experiment 8, with a larger luminance range (0.1-220 cd/m^2). On each of these monitors, subjects reviewed a large number of stimulus pairs and indicated whether or not blobs appeared equally salient. Data show the mean acceptance rates of all patterns computed with a given algorithm (labels on the abscissa), for three classes of blob comparisons. Labels stand for luminance settings predicted from the constant-ratio rule (Weber contrast; "ratio"), the constant-addition rule ("add") in various power transforms (exponents 0.33, …, 1.), and constant luminance differences after normalization to the luminance maximum ("max"); for Dark:Dark and Bright:Bright comparisons, predictions from "max" are identical with predictions from "ratio" and not shown. The label "bg=bg" refers to a subgroup of "ratio" cases with identical backgrounds. Acceptance rates were computed for each subject; bars show the means and s.e.m. across subjects.

0.33"). Predictions from linear ("add 1.0") or nearly-linear luminance differences ("add 0.85", "add 0.71") were here more often rejected than in the standard luminance range.

A more detailed analysis of Experiment 8 is shown in Figure 22. Each stimulus pair was evaluated how well it represented a particular algorithm. Two values might be of particular interest here. One is the accumulated rating of all test conditions that did follow a certain algorithm "alg"; the other is the rating of patterns that did *not* follow this algorithm ("not alg"). The larger this difference, the more likely is salience indeed represented by this particular algorithm. The rating differences between "alg" and "not alg" patterns were particularly pronounced for the constant-ratio predictions of dark blob matches (Fig. 22). About 80% of the patterns that served this algorithm were rated as equally salient (82% with the standard screen, Fig. 22a; 73% with the flatscreen, Fig. 22b), but only very few of the patterns that did *not* serve this algorithm (25% in Fig. 22a; 11% in Fig. 22b). This high correlation suggests that salience of dark blobs is indeed closely related to the computation of constant luminance ratio (Weber contrast). All other ratings were less distinct and computations thus less strongly correlated with salience perception. While some algorithms had received fairly high equal-salience ratings (e.g., "ratio" in the Bright:Dark blob matches), the complementary group of patterns that did not follow this algorithm might also have received high ratings, which would make this algorithm little predictive for salience computations. The opposite is also seen, algorithms that themselves produced low equal-salience ratings, whereas patterns that did not follow these algorithms were, on the average, better rated (e.g., the "ratio" condition in Bright:Bright matches). This would exclude the underlying algorithm from salience

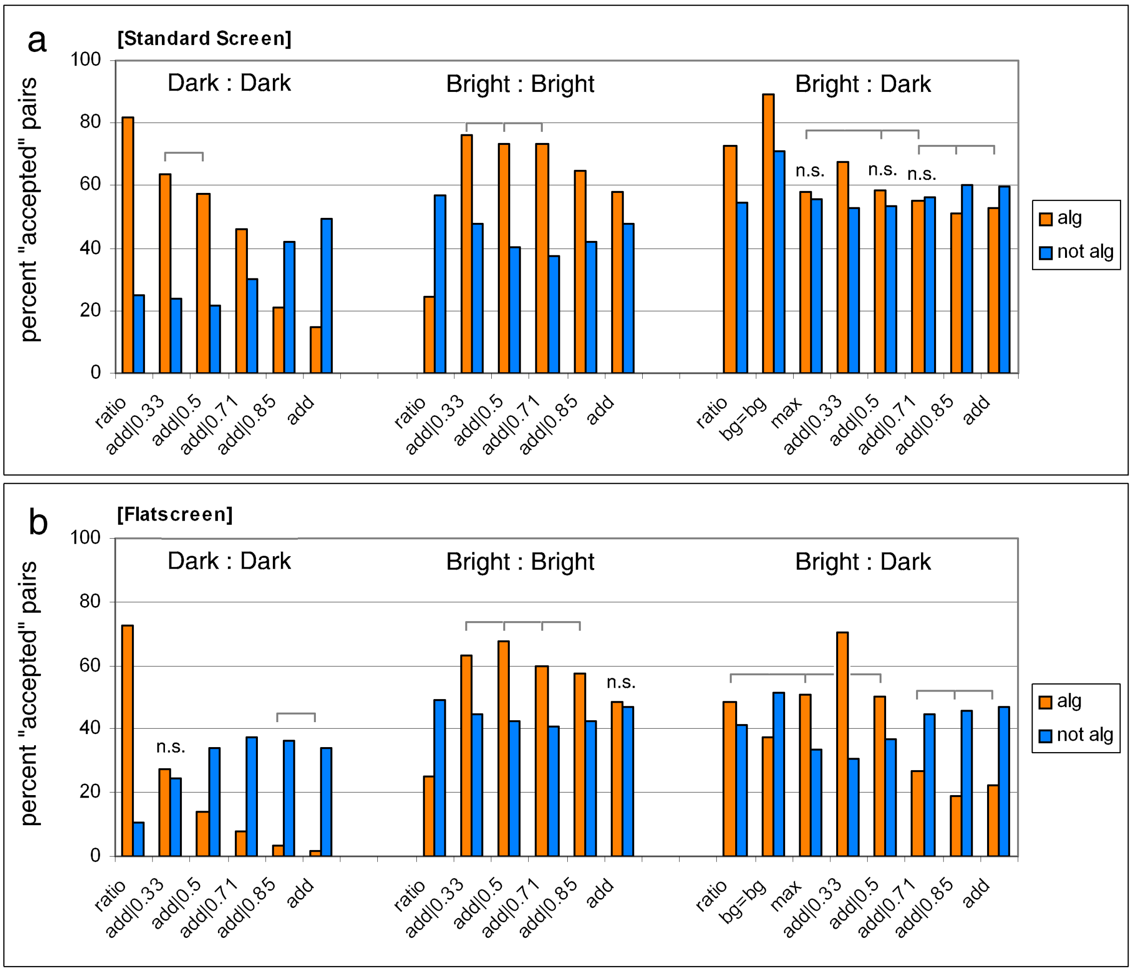

Figure 22. *Grand analysis of equal-salience evaluations across all test patterns in Experiment 8.* **a, b.** Data from different runs on two monitors with different luminance settings, as in Figure 21. For each reviewed stimulus pair, presumed salience measures for various algorithms (abscissa) were computed from the true luminance settings. All pairs, for which these values differed by less than 5% between the two patterns, were taken to represent this algorithm and acceptance rates were accumulated. All pairs, for which these values differed by 20% or more, were assigned to the complementary group of patterns not representing this algorithm, and acceptance rates were also accumulated in this group. (Differences of 5% to 20% were ignored for the analysis with this particular algorithm.) Bars show mean acceptance rates for various algorithm ("alg") and complementary ("not-alg") groups. A strong link of equal-salience ratings to a particular algorithm was only seen for "ratio" in Dark:Dark comparisons, where acceptance rates were high in the "alg" group of test patterns and simultaneously low in the "not alg" group. For many algorithms, the acceptance rates in Bright:Dark matches quite similar for the complementary samples from mutually exclusive groups. Labels are identical to those in Figure 21. The label "n.s." marks "alg":"not-alg" ratings that are not significantly different; squared brackets indicates ratings of different algorithms that were, at least partly, not significant.

computation. Finally, the various ratings for Bright:Dark blob patterns were rather similar, at least on the standard screen, indicating only little correlation of salience with one particular algorithm (Fig. 22a). The similarity of "alg" and "not alg" ratings for so many algorithms suggests that subjects were rather tolerant and had accepted many Bright:Dark patterns as about equally salient. Note that the complementary group to (constant-ratio) "bg=bg" test conditions are (constant-ratio) bg≠bg conditions, which were frequently rated as equal-salient. With the larger luminance range of the flatscreen (Fig. 22b) differences between algorithms were more pronounced. Best ratings and strongest differences between the complementary "alg" and the "not alg" groups were here obtained with the "add|0.33" algorithm that had predicted equal salience on the basis of Stevens' brightness law. Poor ratings were observed for predictions from linear and almost-linear luminance differences ("add", "add|0.85", and "add|o.71").

Significance. Since all ratings were based on large test samples, most differences plotted in Figure 22 are statistically significant; the null hypothesis that two ratings represent data from the same distribution could typically be rejected (*$p<0.05$;* two-sample t-test assuming unequal variances). Only few differences between complementary groups were statistically not significant, as indicated in Figure 22 ("n.s."). This also holds for most rating differences between algorithms. Statistically significant *($p<0.05$)* were, in particular, all differences between the constant-ratio and other predictions *for dark blobs*, the rating differences between power-transformed and either linear constant-addition computations ("add|x" vs. "add") or constant-ratio predictions *for bright blobs,* and the rating differences between the constant-ratio prediction, in particular group "bg=bg", and all other algorithms for *bright vs. dark blob comparisons* in the standard luminance range and between Stevens' brightness law and all other algorithms in the larger luminance range. All groups connected by squared brackets in Figure 22 include ratings that were not significant in certain combinations.

Discussion

There are three surprises in the "confirmation" data. First, no algorithm produced ratings of 100%. This is astonishing given the clear results of equal-salience matches in the previous experiments. Second, ratings of constant-ratio predictions were rather bad for bright blobs. This, too, is surprising given the close overlap of target adjustments with these predictions in Experiment 2 (Fig. 4). Only for dark blob matches were the constant-ratio predictions accepted. For bright blobs, however, better ratings were instead obtained for "not ratio" patterns and, in particular, for computations from constant differences on power-transformed luminance scales. These had indeed fitted some matching data in Experiment 2 (Fig. 4b) but were, in that experiment, generally worse than predictions from the constant-ratio rule (Fig. 4a). The third surprise, finally, is the little modulated ratings of bright vs. dark blob matches. The matches in Experiment 6 and 7 had revealed a fairly strict identity of increments and decrements for equal salience, when blobs were presented on similar backgrounds. This is, beside the constant-ratio prediction for dark blobs, the second finding of the previous experiments that was clearly confirmed in the confirmation task ("bg=bg"). But it was only seen in tests on the standard monitor with a restricted luminance range. When the luminance range was increased (flatscreen), ratings with these patterns were less conclusive. Ratings then showed a slight preference for equal differences on a highly nonlinear luminance scale (Fig. 22b; "add|0.33" and "add|0.5"), which was also found in Experiment 7 when blobs were presented on largely different backgrounds. With the standard luminance settings of the previous experiments (Fig. 21a and 22a), however, observers showed only little preferences for any particular algorithm in bright vs. dark blob matches. These differences were only seen in the larger luminance range (Fig. 21b and 22b).

How can these findings be explained? I have two tentative explanations that stress performance variations and methodological difficulties. Since rating decisions depended on a subjective criterion (which differences do I accept and which ones reject?), there was considerable variation between subjects. In addition, subjects could involuntarily change their criterion and then might have sometimes been searching for differences rather than fairly evaluating the similarity in salience. Subjects also reported that their decisions about equal blob salience were not entirely independent of other perceptual impressions like which pattern appeared brighter (and hence perhaps more salient) or which blob color (dark or bright) was primed as particularly salient from the previous trial (cf. Theeuwes & Van der Burg, 2013). This might have biased subjects in some presentations to accept a pair of blobs that, in fact, looked similarly bright, or reject another pair that was about equal-salient but looked rather different in blob brightness (cf. the demo in Fig. 10). The fact that the preferred ratings of bright blob matches, particularly those with large luminance variations, tended to follow Stevens' brightness law may indicate the large influence of brightness effects in these ratings, that was perhaps less dominant in the earlier matches of Experiments 1-6.

But that should not weaken the findings of Experiment 8. It is difficult to avoid such methodological limitations. If salience itself is measured and not a functional aspect of it, it may be difficult to exclude subjective criteria, and there is virtually no way around priming effects in such studies. My own impression from that experiment is that one often can clearly rate two blob patterns as equally salient and two others as clearly not equally salient. The fact that these observations do not sum up to 100% with one algorithm, or to 0% with another one, does not weaken the measurements but more likely the conclusion that one particular algorithm would be the true and only salience algorithm for all conditions.

FINAL CONCLUSIONS

With the results from Experiment 8 we must now update and partly revise the earlier generalizations above. Over all experiments, there were several consistent but also some variable findings about the computation of luminance-defined salience in homogeneous blob arrays.

For *dark blobs*, equal salience estimates are well predicted by constant-ratio computations, i.e. by the Weber contrast of items to background; minor variations are seen from brightness contrast and assimilation effects. This observation was consistently made in all related experiments.

For *bright blobs*, the pattern was less consistent. While matches of bright blobs that were dimmer than the constant reference also followed the Weber contrast, this was not the case when blobs to be adjusted were notably brighter than other items. Matches could then be additive, i.e. requiring the same luminance difference to background to make blobs look equally salient. The general preference over a large variation of patterns, however, seems to relate equal salience to Stevens' brightness law and to constant differences in the power of luminance, with exponents around $x=0.5$.

Salience matches of *bright and dark blobs,* finally, strongly depended on the according background luminance settings. When blobs were presented on same backgrounds, subjects matched them for equal deviations from these backgrounds (increments = decrements) and only diminished these settings for blobs of large contrast. When blobs were presented on different backgrounds, however, matches again followed Stevens' brightness law with an exponent around $x=0.5$.

Altogether, this leaves a considerable uncertainty about salience computation and about which blob patterns (or single items) would appear equally salient. Whether this uncertainty is indeed leaving salience itself variable and partly uncertain, or whether certain functions are related to only one algorithms, and other functions perhaps to another one, needs to be investigated.

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