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Lightness effects in Delboeuf and Ebbinghaus size-contrast illusions

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Abstract. We examined lightness effects observed in Delboeuf and Ebbinghaus size-contrast illusions. Results of four experiments are reported. Experiment 1 was conducted with Delboeuf-like stimuli and shows that the disk that appears bigger appears either lighter or darker than the disk that appears smaller, depending on the contrast polarity between disks and background. Experiment 2 shows that the direction of these lightness effects is not influenced by the luminance of the size-contrast inducers. Experiment 3 shows that a similar lightness effect is also observed in modified Ebbinghaus size-contrast displays. Experiment 4 tested the presence of the size-contrast illusion in the stimuli used in experiments 2 and 3.

1 Introduction

It is well known that the phenomenal size of a surface does not depend only on the dimension of its retinal projection but also on the surrounding context. In particular, in one version of the Delboeuf (1865, 1893) illusion, the apparent size of two disks is modulated by the sizes of outer concentric circles: a big concentric circle makes an inner disk appear smaller, while a small concentric circle makes an inner disk appear bigger (figure 1). Vicario (1972) showed that the illusion has also an effect on the perceived density of textures: when two equal textured targets are placed inside Delboeuf-like displays, the one that looks bigger appears also to be more rarefied.

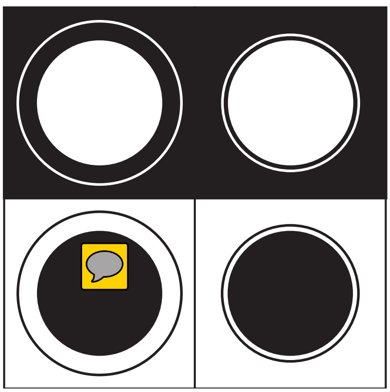


Figure 1. Reproduction of some of the original configurations employed by Delboeuf (1865).

A lightness effect was also recently observed (Zanuttini and Daneyko 2010; Zanuttini et al 2009) in the Delboeuf illusion consisting of two white disks, equal in size and luminance, seen against a dark background and, respectively, concentric with two circles of different diameters. In such a configuration the disk that appears bigger appears lighter than the disk that appears smaller.

In the present study we further investigated the phenomenon described by Zanuttini and Daneyko (2010) by considering achromatic disk targets that were either increments or decrements to their background.

2 Experiment 1. Increments and decrements

In our previous study (Zanuttini and Daneyko 2010) we only employed white disks on darker backgrounds. In the present study we employed grey disk targets on either dark or light backgrounds. Hence, the two targets viewed simultaneously in Delboeuf-like displays were either luminance increments or luminance decrements with respect to the background. With increment targets we expected to find that the target that appears bigger would also appear lighter than an identical target that appears smaller (Zanuttini and Daneyko 2010). Decrement targets, instead, could lead to one of the following outcomes:

—no effect on the lightness of the targets (the two targets appear to be of the same shade of grey);

—the target that appears bigger appears also lighter, as found with increment targets in the previous study;

—the target that appears bigger appears also darker (the opposite of what is found with increment targets).

2.1 *Methods*

2.1.1 *Participants.* Twenty-nine graduate and undergraduate students (aged 18 – 33 years; twenty female and nine male) from the University of Milano-Bicocca volunteered to take part in the experiment. All participants had normal or corrected-to-normal vision and all were naive with respect to the purpose of the study.

2.1.2 *Stimuli.* Stimuli consisted of two targets—one surrounded by a large concentric circle, the other surrounded by a small concentric circle—presented either on a dark or a bright background (figure 2).

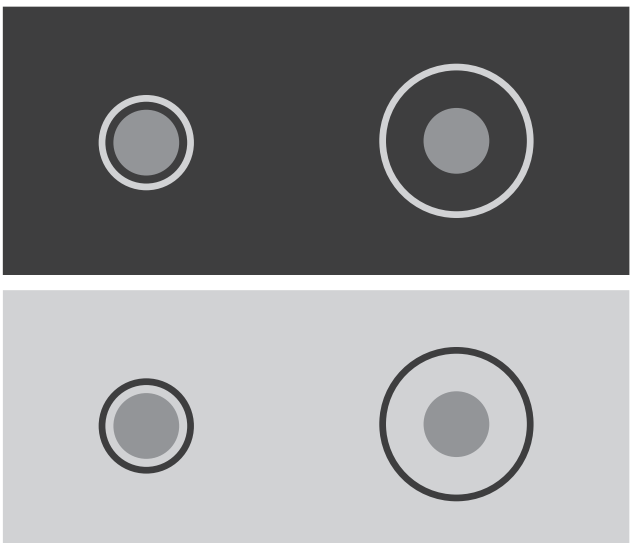


Figure 2. Example of the modified Delboeuf configurations used in experiment 1: increment targets (top) and decrement targets (bottom).

Configurations measured 21 cm × 7.5 cm (length × height, 10.43 deg × 3.76 deg) and were printed on heavy-weight matte paper with an Epson Stylus Photo R2400 printer. Disk targets measured 2 cm in diameter (1 deg); the small and the large outlined concentric circles (inducers, line width = 0.2 cm) measured, respectively, 3.2 cm (1.6 deg) and 5.2 cm (2.6 deg) in diameter. The width of the gap between the target and the inducer was 0.35 cm (0.17 deg) with small inducers and 1.34 cm (0.67 deg) with large inducers. Disks were viewed in pairs; each disk in a configuration could have one of the following luminance values: 136, 145, 158, 167, 171, 178, 200 cd m^{-2}; background luminance was either 45.7 or 444 cd m^{-2}. The luminance of the inducers was 444 cd m^{-2} on the dark background, and 45.7 cd m^{-2} on the bright background. The combination of disk luminance and background luminance resulted in 49 pairs of targets for each background.

2.1.3 *Procedure.* Stimuli were presented in a dim room and were viewed at a distance of 114 cm. Illumination was provided by a theatrical spotlight pointed at the stimuli. Stimuli were viewed only once and were randomly presented right-side-up or upside-down, so that the disk that appeared bigger could be either on the left or on the right side of a configuration. A forced-choice task with a within-group design was employed. Participants were instructed to indicate in each configuration which disk appeared darker: left or right.

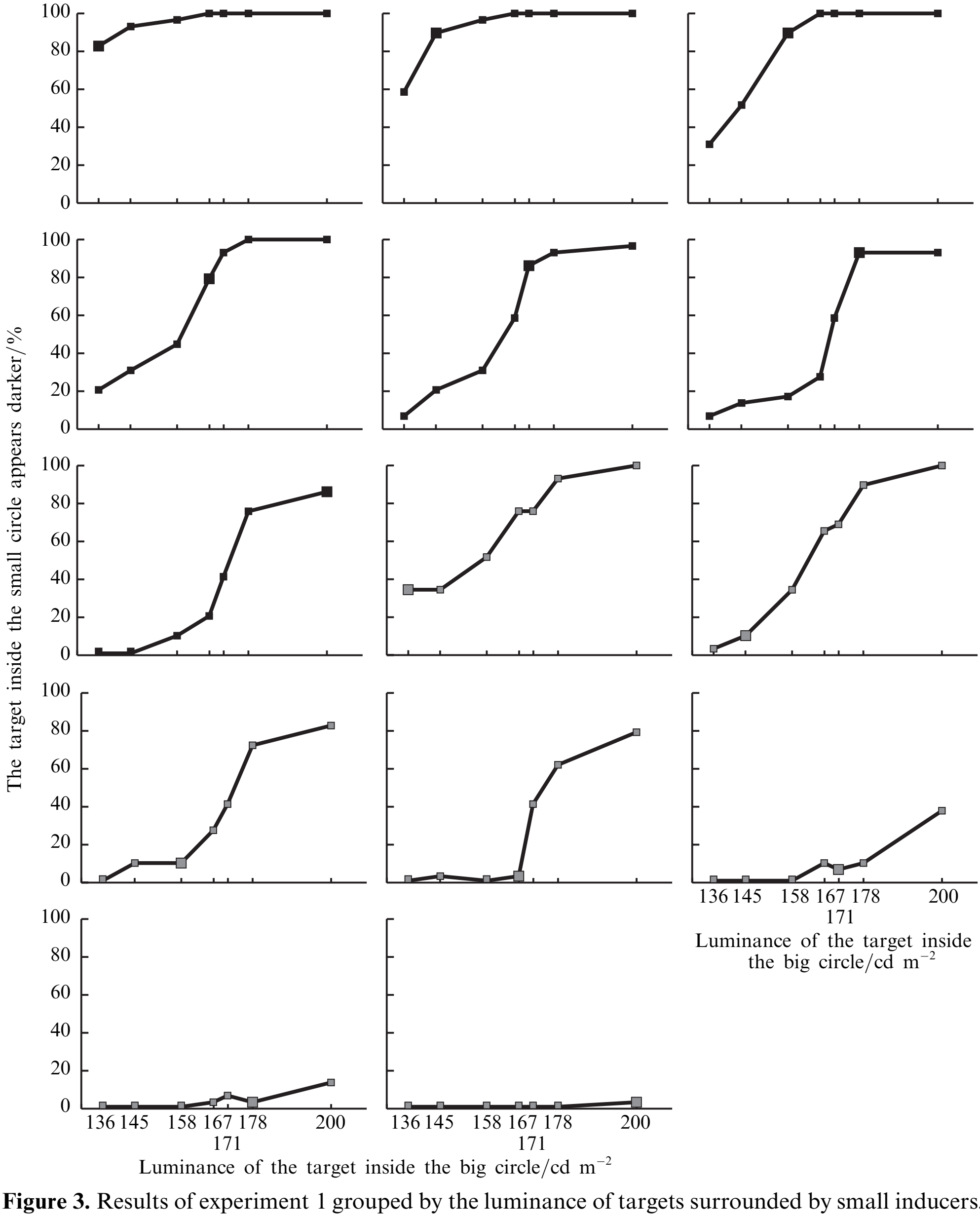


Figure 3. Results of experiment 1 grouped by the luminance of targets surrounded by small inducers. Black squares indicate decrement targets, grey squares increment targets; the larger square in each graph indicates both the luminance of the target surrounded by small circles and the condition in which two targets shared the same luminance.

2.2 *Results*

Figure 3 displays the results for increment and decrement targets grouped by luminance comparisons. Table 1 provides the results of χ^2 tests performed on the data for configurations in which targets had equal luminance.

Increment and decrement targets produced opposite results when targets were equal in luminance: the target that appeared bigger appeared lighter when it was an increment to a dark background, and darker when it was a decrement to a bright background. This finding can also be summarised as follows: in all configurations with targets of equal luminance, the target surrounded by a small inducer was always seen as more contrasted to the background, independently of the target contrast polarity.

Table 1 χ^2_1 tests (*p*-values with Bonferroni correction for target pairs of equal luminance).

	Luminance pairs/cd m^{-2}						
	136	145	158	167	171	178	200
Increments							
χ^2	9.96	18.24	18.24	25.13	21.55	25.13	25.13
p	0.014	<0.0007	<0.0007	<0.0007	<0.0007	<0.0007	<0.0007
Decrements							
χ^2	12.44	18.24	18.24	9.96	15.2	21.55	15.2
p	<0.0007	<0.0007	<0.0007	0.014	<0.0007	<0.0007	<0.0007

2.3 *Discussion*

Results for increment targets are consistent with those obtained in a previous study (Zanuttini and Daneyko 2010): when the targets in a stimulus have the same luminance, the target that appears bigger appears also lighter. Decrement targets show opposite results: when targets are equal in luminance, the target that appears bigger appears darker. This consistent difference between increment and decrement stimuli may depend on two factors: (i) the polarity of target – background contrast, and/or (ii) the luminance of the size-contrast inducers (circumscribing circles), which were bright in increment displays (dark backgrounds) and dark in decrement displays (light backgrounds)—see figure 2.

3 Experiment 2. Testing the role played by the luminance of the size-contrast inducers

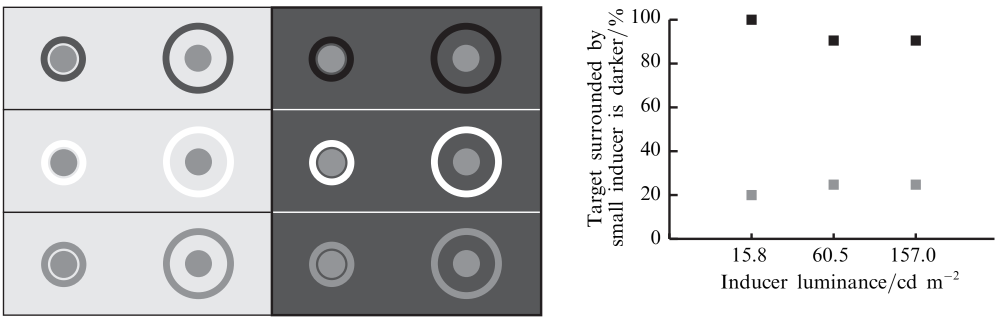
In experiment 2 we manipulated the luminance of the circles circumscribing the two targets in both increment and decrement displays: inducer pairs could be black, white, or mid-grey. This manipulation may be of some interest for edge integration models, given that these models might predict an effect of edge luminance on the appearance of the two targets. The story could go roughly as follows: the stimuli used in experiment 1 would comprise two sets of inducers: two remote inducers—in our case the size-contrast inducers (alias circles), and two local inducers (the portion of background shaped like a ring surrounding the target). The remote inducers cause the darkening (dark backgrounds) or the brightening (bright backgrounds) of the local inducers, which would then affect the appearance of the targets. In our stimuli, the lightness difference between the two targets of equal luminance would be caused by the width of the local inducer: a small width should facilitate brightness filling-in (Rudd and Arrington 2001). The small local inducer would be therefore either darker or lighter than the large local inducer, depending on the contrast polarity between remote and local inducers. This difference would also translate to the target surrounded by the small local inducer, causing its darkening if the target is a decrement, or its brightening if it is an increment. May be, edge-integration theorists would tell a more detailed, or even a different, story, but then they should predict different outcomes in experiments in which the luminance of the size-inducing circles is varied with respect to the values used in experiment 1.

3.1 *Methods*

3.1.1 *Participants.* Twenty-one participants from Tohoku Gakuin University in Sendai (aged 17–55 years; ten female, eleven male) volunteered to take part in the experiment. All participants had normal or corrected-to-normal vision.

3.1.2 *Stimuli.* Stimuli (figure 4) were similar to those employed in experiment 1 except for the following features: (i) targets had all the same luminance (60.5 cd m^{-2}); the luminance of pairs of inducers (concentric circles) was 186 cd m^{-2} (white), 60.5 cd m^{-2} (mid-grey), or 10.6 cd m^{-2} (black) on both dark (15.8 cd m^{-2}) and bright (157 cd m^{-2}) backgrounds. The combination of inducer luminance and background luminance determined six configurations labelled: dW, dB, dG, iW, iB, and iG (figure 4).

3.1.3 *Procedure.* The procedure was the same as in experiment 1.



(a) (b)

Figure 4. (a) From top to bottom and left to right, stimuli dB, dG, dW, iB, iG, and iW used in experiment 2. (b) Results of experiment 2: black squares denote decrement targets, grey squares denote increment targets.

3.2 *Results*

Figure 4 displays the results of experiment 2. $\chi^2_{1,21}$ tests were carried out (except for stimulus dB, in which the target surrounded by a small inducer was chosen as darker by all participants), confirming a significant difference between the lightness appearance of each pair of targets: $\chi^2_{\mathrm{iW}} = 8.05$, $p < 0.005$; $\chi^2_{\mathrm{iB}} = 5.8$, $p < 0.05$; $\chi^2_{\mathrm{iG}} = 5.8$, $p < 0.05$; $\chi^2_{\mathrm{dW}} = 13.8$, $p < 0.0001$; $\chi^2_{\mathrm{dG}} = 13.8$, $p < 0.0001$. Two Cochran's Q tests were carried out to verify whether the proportions were the same across configurations with the same background luminance and different inducer luminance (degrees of freedom 2, $N = 21$); no significant differences were found: dark backgrounds, $Q = 0.3$, $p = 0.8$; light backgrounds, $Q = 2.6$, $p = 0.2$.

3.3 *Discussion*

The results of experiment 2 show that the luminance of the size-contrast inducers is not an effective variable for the lightness effects observed: the effects are comparable to those obtained in experiment 1, regardless of the contrast polarities inside each stimulus.

Edge-integration models (Reid and Shapley 1988; Rudd and Zemach 2004, 2005; Shapley and Reid 1985; Vladusich et al 2006) cannot account for the results of experiment 2 without becoming more complex. Such models, in fact, would eventually predict different results depending on the contrast polarities between edges. It is not immediately obvious, however, whether more sophisticated models in their current form (Rudd 2010; Rudd and Popa 2007; Rudd and Zemach 2007) could account for all the data.

On the other hand, the findings of experiment 2 represent a challenge for any model that assumes effects to be caused always by luminance relations between targets and 'inducers'. Such models would end up either predicting contrast or assimilation based on the luminance ratios within the fixed geometry of our configurations. Yet the direction of the effects in the Delboeuf displays appears to be affected only by the luminance of the backgrounds, and not by the luminance of the size-contrast inducers. In other words, the target surrounded by a small inducer always appears more contrasted to the background than the target surrounded by a large inducer, and this regardless of inducer – background and inducer – target luminance contrast polarities.

4 Experiment 3. Ebbinghaus-like displays

In experiment 3 we set out to verify whether the lightness effects observed in the Delboeuf-like displays can also be observed in the Ebbinghaus size-contrast illusion. The basic configuration of this illusion consists of two targets (in our case grey disks) each surrounded by a group of six circles (inducers). One target is surrounded by inducers smaller than it, while the other target is surrounded by inducers bigger than it (figure 5). As in the Delboeuf illusion, the target surrounded by small inducers usually appears bigger than the target surrounded by large inducers.

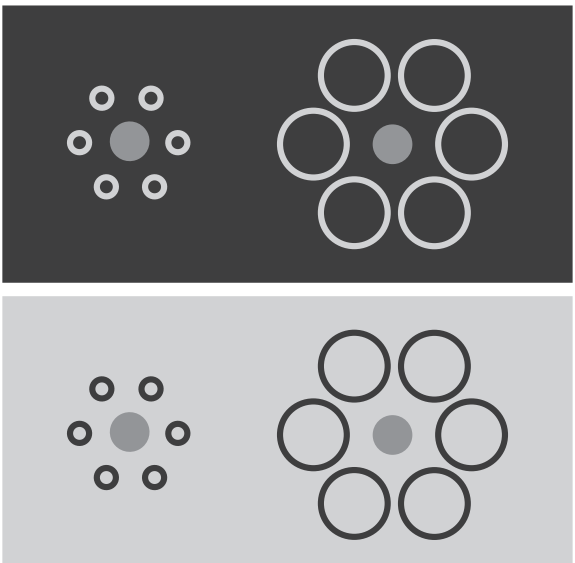


Figure 5. Modified Ebbinghaus displays with increment targets (top) and decrement targets (bottom).

In our new configurations we kept the orthogonal distance between targets and sets of inducers equal (ie the perpendicular distances between the nearest pair of parallel tangents to an inducer and a target were equal for both targets), which translated into configurations in which the distance between small inducers and target is relatively larger than usually found in textbook versions of the illusion. Previous work has shown that the magnitude of the Ebbinghaus illusion decreases as a function of the distance between the inducers and the targets (Ehrenstein and Hamada 1995; Roberts et al 2005). This issue will be addressed in experiment 4.

4.1 *Methods*

4.1.1 *Participants.* Ten graduate and undergraduate students from the University of Milano-Bicocca (aged 18 – 29 years; five female, five male), who did not participate in the previous experiments and who were unaware of the purpose of the study, volunteered to take part in the experiment. All participants had normal or corrected-to-normal vision.

4.1.2 *Stimuli.* Stimuli were 26 configurations created with the same material as described in experiment 1. Configurations measured 29 cm × 13.5 cm (14.2 deg × 6.7 deg). Disk targets measured 2 cm in diameter (1 deg). Configurations (figure 5) showed two targets, one surrounded by six small circles (small inducers, diameter 0.8 deg) and the other surrounded by big circles (big inducers, diameter 1.8 deg). The perpendicular distance between a target and its inducers was the same for big and small inducers (0.65 deg). The luminance values of the targets were: 136, 145, 158, 167, 171, 178, and 200 cd m^{-2}; however, in all configurations one of the two targets always had a luminance of 167 cd m^{-2}. Background luminance was either 45.7 cd m^{-2} or 444 cd m^{-2}. On the dark background the luminance of the inducers was 444 cd m^{-2}; on the bright background it was 45.7 cd m^{-2} (figure 5).

4.1.3 *Procedure.* The procedure was the same as in experiment 1.

4.1.4 *Results and discussion.* Figure 6 shows the results of comparisons with decrement and increment targets 167 cd m^{-2} surrounded by small (top) and large (bottom) inducers. As one can readily see, when paired targets both measured 167 cd m^{-2}, the increment target that appears bigger appears also lighter, while the decrement target that appears bigger appears also darker. We compared the data of experiment 3 with the data of experiment 1 for similar luminance target configurations with a Kurskal–Wallis H test (1 degree of freedom; twenty-nine subjects for experiment 1; ten subjects for experiment 3) and found no significant difference for increment and decrement targets ($0.09 \leqslant p \leqslant 1$).

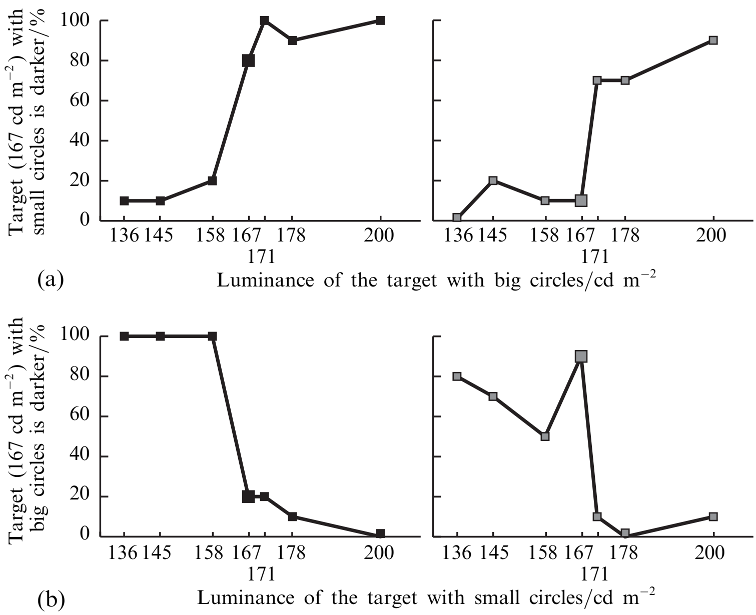


Figure 6. Results for experiment 3. Black squares stand for decrement targets, grey squares for increment targets; larger squares indicate the condition in which the luminance of both targets was 167 cd m^{-2}.

Results are consistent with those of experiments 1 and 2, and support the hypothesis of a relationship between the size-contrast effect and the lightness effects in the Delboeuf and the Ebbinghaus size-contrast illusions.

5 Experiment 4. Is the size-contrast effect still there?

In experiment 2 we manipulated the luminance of the inducers and found that this variable does not affect the outcome of the lightness illusion in Delboeuf-like displays. These manipulations, however, may affect the magnitude of the size-contrast effect. While Cooper and Weintraub (1970) concluded that the luminance of the inducers is an ineffective variable, Jaeger and Lorden (1980) reported that the magnitude of the size-contrast illusion is a function of the lightness contrast between the inner circle and the outer circle in Delboeuf-like displays made of concentric circles. Nevertheless, their findings did not show a systematic pattern.

In an earlier study, Oyama (1962) reported that the magnitude of the Delboeuf size-contrast illusion is, instead, a function of inducer-background luminance contrast: the illusion is stronger when the contrast is greater. Similar findings were reported also by Wada (1956), Weintraub and Cooper (1972), and Jaeger and Long (2007). If Oyama is right, our luminance manipulations in experiment 2 could have affected the magnitude of the size-contrast illusions, reducing it, if not actually hindering it, when the contrast ratio between the inducer and the background was low, as in the case of stimuli iB and dW (figure 4).

In experiment 3 we used Ebbinghaus-like stimuli in which the space between the target and the small inducers was greater than usually found in textbook versions of this illusion (see, for example, Palmer 1999, figure 1.1.4, page 8). It has been shown that this factor is relevant for the magnitude of the size-contrast illusion (Ehrenstein and Hamada 1995; Roberts et al 2005). The question is, therefore, whether the size-contrast illusion is still present in our displays.

Experiment 4 was conducted to test the presence (not the magnitude) of size-contrast illusions in the displays used in experiments 2 and 3. Such presence is relevant for the interpretation of the findings of our previous experiments (see section 6).

5.1 *Methods*

5.1.1 *Participants.* Eleven members of the psychology department (aged 26–47 years; seven female, four male), who did not participate in the previous experiments and who were unaware of the purpose of the study, volunteered to take part in the experiment. All participants had normal or corrected-to-normal vision. Three out of five of the older subjects were familiar with these size-contrast illusions, while only one of the younger participants was familiar with the Ebbinghaus illusion, and none was familiar with the Delboeuf illusion.

5.1.2 *Stimuli.* The set of stimuli comprised those used in experiment 2 (figure 4) plus two of the stimuli used in experiment 3 (the ones in which the two targets had the same luminance). Stimuli were displayed in a viewing chamber (for specifications see Zavagno and Daneyko 2008) at a distance of 57 cm. Luminance values were the following:

— Delboeuf stimuli (iG, iW, iB, dG, dW, and dB): targets = 13.6 cd m^{-2}; grey inducers = 13.6 cd m^{-2}; white inducers = 50.27 cd m^{-2}; black inducers = 1.7 cd m^{-2}; dark background = 3.5 cd m^{-2}; bright background = 37.2 cd m^{-2}.

— Ebbinghaus stimuli (iE and dE): targets = 16.21 cd m^{-2}; dark inducers and dark background = 3.5 cd m^{-2}, bright inducers and bright background = 37.2 cd m^{-2}.

5.1.3 *Procedure.* Targets were presented in random order, right-side-up or upside-down. Participants were asked to report which of two targets appeared bigger in a forced-choice task.

5.2 *Results and discussion*

The results are displayed in figure 7. As one can see, the results confirm the presence of the size-contrast illusions in all our displays. Two of the observers who were familiar with the Ebbinghaus illusion spontaneously commented that they can clearly see a size difference, but they also added that the effect was somewhat weaker than what they remember it to be. One of the younger participants commented that the experiment was "too easy" because all of the effects were "too strong", except in one case, stimulus iB (figure 4, top right) for which he indicated the target surrounded by the big black inducer as biggest.

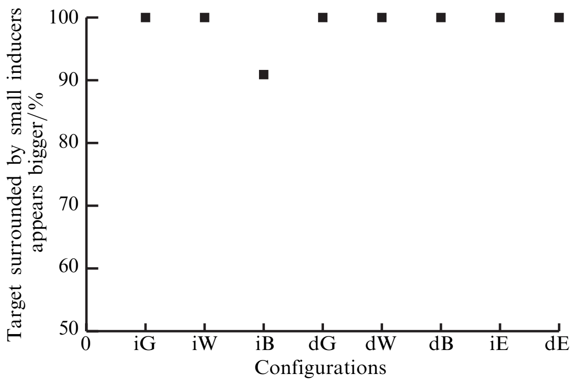


Figure 7. Results of experiment 4.

While this experiment did not test the magnitude of the size-contrast illusions in our displays, it confirmed that the illusions are present, thus allowing us to hypothesise a relationship between the size-contrast effects and the lightness differences observed.

6 Conclusions

Results from all four experiments allow us to hypothesise a relationship between the size and the lightness effects in the Delboeuf and the Ebbinghaus size-contrast illusions. At the moment we cannot confirm the existence of a causal effect of size on lightness in the displays employed in this series of experiments.

Nevertheless, evidence in support of a relationship between perceived size and lightness has been found in an experiment that made use of stimuli presented stereoscopically (Daneyko and Zavagno 2010). Stimuli consisted of pairs of squares that were physically different in size (the area of the small target was about a third of the area of the other target) but were always perceived as coplanar: when the two targets had the same luminance, the bigger target appeared systematically more contrasted to the background, that is lighter than the smaller target when targets were increments, and darker when they were decrements. The magnitude and the polarities of the effects are consistent with the lightness effects reported in experiments 1, 2, and 3. It is also fundamental to stress that the results of the aforementioned experiment were found with configurations consisting of only two targets, without any type of inducer.

Experiments still need to be carried out to assess the nature and the extent of a hypothetical relationship between perceived size and lightness in size-contrast illusions. Yet, if we consider the results from the experiments presented in this study (in which stimuli differed in size only perceptually) along with the results presented by Daneyko and Zavagno (2010) (obtained with stimuli that actually differed in size), we feel it is fairly safe to hypothesise that a perceived size difference between two targets of equal luminance can induce a lightness difference between targets, resulting in greater perceived contrast between background and the target that appears bigger.

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