

Perceptual grouping leads to objecthood effects in the Ebbinghaus illusion

Einat Rashal

Laboratory of Psychophysics, Brain Mind Institute, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland



Aline F. Cretenoud

Laboratory of Psychophysics, Brain Mind Institute, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland



Michael H. Herzog

Laboratory of Psychophysics, Brain Mind Institute, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland



The Ebbinghaus illusion is argued to be a product of low-level contour interactions or a higher cognitive comparison process. We examined the effect of grouping on the illusion by manipulating objecthood, i.e., the degree to which an object is a cohesive perceptual entity. We hypothesized that reduced objecthood would decrease the illusion magnitude, because the objects become less efficient in the comparison process. To test this hypothesis, we used a version of the illusion where the target and flanking objects were squares that were composed from their corners or sides. Degree of objecthood was manipulated by changing the gap size or rotation angle of the elements constructing the objects, so that larger gaps and angles produced less cohesive objects than smaller. Participants performed an adjustment procedure on the test target to match a control target in size. In addition, subjective reports of the objects' shape were collected as a measure of perceived shape. Our results show decreased illusion magnitude with increasing gap size and rotation angle. Surprisingly, the perceived shape of the objects did not correlate with illusion magnitude. These results provide novel evidence of the role of mid-level processes in the Ebbinghaus illusion and point to a dissociation between subjective and objective measures of objecthood.

Coren & Enns, 1993; Coren & Miller, 1974; Massaro & Anderson, 1971; Vuk & Podlesek, 2005), whereas the latter poses that the target is perceived as stretched or contracted because the target's contours are attracted or repulsed by the contours of the flankers (e.g., Jaeger, 1978; Jaeger & Klahs, 2015; Sherman & Chouinard, 2016; Schwarzkopf & Rees, 2013; Todorović and Jovanović, 2018; Weintraub & Schneck, 1986).

An important distinction can be made between the two accounts: the first would have to consider some qualities of the objects available for comparison, whereas the second is more concerned with the position of contours around the target. To provide good standards for the comparison, the flankers should give ample evidence that they are similar to the target. Such evidence comes, for example, from their number and their distance, because a larger number of flankers provides more information, and the closer the flankers are to the target the more relevant they are for the comparison (Massaro & Anderson, 1971). Shape was suggested to play a role as well, because flankers and targets with similar shapes can be better compared than objects with different shapes (Coren & Miller, 1974). On the other hand, for contour interactions to occur, contours should be strategically located in close and far positions relative to the target to affect its size perception (e.g., Jaeger, 1978).

A recent study by Jaeger and Klahs (2015) tested the relative strengths of the two accounts by studying the effect of the number of flankers on the illusion. In that study, a few small flankers surrounded the target and as the number of flankers increased, they led to circular configurations (i.e., with the maximum number of flankers, the target was flanked by large circular groups of small circles). The authors reasoned that increasing the number of small flankers would result in an increase of illusion magnitude (i.e., the target will appear

Introduction

In the Ebbinghaus illusion, a target looks smaller when it is surrounded by larger flanking objects or looks bigger when it is surrounded by smaller ones. This phenomenon has been offered two accounts: a cognitive size contrast mechanism or low-level contour interactions. The former proposes that the size of the target is judged in comparison to the size of the surrounding stimuli (e.g., Choplin & Medin, 1999;

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even larger) according to the size contrast account, because of the increasing salience of the standard in the comparison. On the other hand, according to the contour interaction account, this manipulation would cause the illusion to change direction (i.e., the target will appear to be larger and then decreasing in size with increasing number of small flankers), as repulsion will be generated from the flankers on the outer perimeter of that configuration as small flankers are added. Their results supported the second hypothesis, replicating a similar switching effect reported by Weintraub and Schneck (1986), who manipulated the length of flanking contours, starting from small arcs and progressing onto full large flanking circles. In both studies, this effect was interpreted as evidence in favor of the contour interaction account, however, as mentioned by Jaeger and Klahs (2015), the switch in direction could have been due to the larger circular configurations effectively functioning as large flankers, in which case, the effect can be explained by the size contrast account as well.

Influence of mid-level organizational process such as the grouping of small flankers reported in Jaeger and Klahs (2015) would support the cognitive size contrast account and challenge the low-level contour interaction account. However, the role of perceptual organization in the Ebbinghaus illusion has not been tested directly yet. In the current study, we examined the effect of mid-level processes on the Ebbinghaus illusion by measuring the effect of *objecthood* on the illusion magnitude, objecthood being the degree to which an object is a cohesive perceptual entity. We theorized that a degraded object would be less efficient in the comparison. Objecthood was defined in terms of grouping strength between object parts—stronger grouping leads to more cohesive objects (Kimchi, Yeshurun, Spehar, & Pirkner, 2015). In our experiments, we presented observers a variant of the classic Ebbinghaus illusion using square target and flankers. Objecthood was manipulated by varying the percentage of the visible contour of the squares (Experiments 1–3), or the rotation angle of the elements constructing the squares (Experiment 4). Importantly, the visible contour of the flankers was presented in a way that the ratio between close and far contours relative to the target did not change (relative to the center of each flanker). According to the contour interaction account, varying objecthood in this way should not change the illusion magnitude, as the ratio between attraction and repulsion from the flankers' contours on the target does not change¹. However, according to the size contrast account, a decrease in visible contour should lead to a weaker illusion because the objects would become less “object-like.” This would make the comparison less effective since the objects would become less similar. Thus our hypothesis was that the illusion would be weaker with decreasing objecthood of either the target or the flankers. Specifically, the illusory

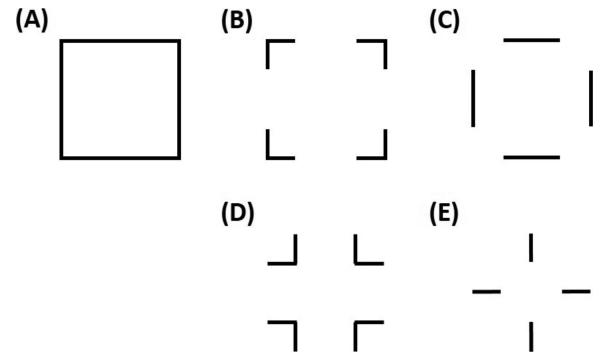


Figure 1. Example stimuli employed in Experiments 1–3: Complete square (A), square constructed by corners (B), and square constructed by sides (C). In Experiment 3 flankers had a cross-like shape constructed by corners (D), or lines (E). Note that illustrations B–E depict the objects with a gap size of 0.5 (see text for details).

effect on the estimation of target size should decrease with a decreasing percentage of visible contour or with increasing rotation angle.

Experiment 1

Our first experiment was designed to establish whether an objecthood effect can be found on the Ebbinghaus illusion using squares with a gap-size manipulation. To that end, we manipulated the percentage of visible contour of either the target or the flankers. Using squares allowed us to manipulate objecthood also by means of different grouping cues (Figure 1). Collinearity between object segments, like the corners of a square, contributes to a stable representation of the shape (Kimchi et al., 2015; Hadad & Kimchi, 2008). Thus, if the illusion is sensitive to objecthood, there may be a difference between conditions displaying squares made of corners or squares made out of sides. That is, the illusion magnitude may decrease to a different degree when the target is composed of corners or surrounded by flankers composed of corners compared with when it is composed of sides or surrounded by flankers composed of sides.

Corners are also powerful in carrying shape information (e.g., Persike & Meinhardt, 2017; Poirier & Wilson, 2007). Because it is difficult to disentangle shape from objecthood—low objecthood will almost certainly lead to a degraded perception of the object's shape—there may be a correlation between the perceived shape of the object and the magnitude of the size illusion. To test this, we also collected subjective reports of shape and objecthood of the different objects in the displays. We hypothesized that

the percentage of visible contour and element type (i.e., sides/corners) would affect the perceived shape of the object. Specifically, we expected a decreasing percentage of “square” reports with decreasing percentage of visible contour and a difference in the reports between objects made of corners or made of sides.

Method

Participants

Ten naïve students from the École Polytechnique Fédérale de Lausanne (EPFL) participated in this experiment (three females; mean age: 21.40 years; range 18–26 years). Participants signed informed consent forms and were paid for their participation. Procedures were conducted in accordance with the Declaration of Helsinki (except for preregistration) and were approved by the local ethics committee.

Apparatus

Participants sat at a distance of ≈ 57 cm from the screen. Stimuli were presented on a BenQ XL2420T monitor driven by a PC computer using Matlab (R2014b, 64 bits) and the Psychophysics toolbox (Brainard, 1997; Pelli, 1997; version 3.1, 64 bits) at a 1920- × 1080-pixel resolution with a 60-Hz refresh rate. Participants used a Logitech LS1 computer mouse to adjust stimuli on the screen. The screen luminance was measured and controlled before the experiment with a Minolta LS-100 luminance meter.

Stimuli

The stimuli were based on a square version of the Ebbinghaus illusion (Figure 2, top panel). The squares were presented in white (≈ 176 cd/m²) with a stroke width of two pixels on a black background (≈ 1 cd/m²). Following previous studies (e.g., Cretenoud, Karimpur, Grzeczowski, Francis, Hamburger, & Herzog, 2019), targets were positioned 8.6° from the center of the screen on both sides. A configuration on the left depicted the *reference target* (i.e., a square surrounded by smaller squares), and it was centered at 2.45° above the medial axis of the screen. The configuration on the right depicted the *test target* surrounded by larger flankers, centered at 2.45° below the medial axis of the screen. The misalignment on the horizontal meridian was designed to prevent participants strategically drawing imaginary lines between the outlines of the target and reference. The reference target subtended 2.45° on each side and was surrounded by eight smaller squares subtending 1.22° on each side. The center-to-center distance between target and flankers in the reference configuration was 2.6°. The test target was

surrounded by six flankers subtending 3.18° on each side, with a center-to-center distance of 4.5°.

The test target or the flankers in both configurations were composed of complete or incomplete squares. The incomplete squares were constructed from separate L-shaped elements (i.e., corners) or lines (i.e., sides), forming a square by means of grouping operations (see Figure 1). In each display, when the test target was an incomplete square, the flankers (in both test and reference configurations) were complete squares, and when the test target was a complete square the flankers were incomplete squares. In conditions where the squares were incomplete, the percentage of visible contour was between 10–90%. The gap size between the segments of visible contour varied in steps of 10% on each side of the square. Example stimuli in Experiment 1 with minimum (0.1) and maximum (0.9) gap size can be found in the Supplementary File (Supplementary Figure S1). Where corners were presented, gaps were formed from the centers of the square’s sides, increasing in size symmetrically towards the corners of the square. Where sides were presented, gaps were formed in the same manner from the corners of the square toward its center. The reference target was always a complete square, to prevent participants from adopting a strategy in which they matched the gap size on one side of the targets instead of the overall size of the object.

Procedure

Adjustment task

Before displaying the stimuli on the computer screen, the experimenter explained the task to the participant using a paper drawing of the illusion. Participants were instructed to base their adjustments only on their subjective perception.

Participants had to match the size of the test target to the size of the reference target. The factor of object role (i.e., target/flankers as incomplete squares) was manipulated between blocks. The factor of element type (i.e., corners/sides) was manipulated independently. Hence, in one block, the test target was a “*corners-target*” or a “*sides-target*” (i.e., a square composed of corners or sides, respectively; Figures 2A and 2B). In another block, the flankers were incomplete squares; “*corners-flankers*” consisting of corners, or “*sides-flankers*” consisting of sides (Figures 2C and 2D). The latter also included a condition where the targets were presented without flankers, and a baseline condition with complete squares only. The order of the blocks was randomized between participants. Gap size and element type were chosen randomly within a block, with a restriction that two consecutive adjustments were made on the exact same condition (e.g., flankers

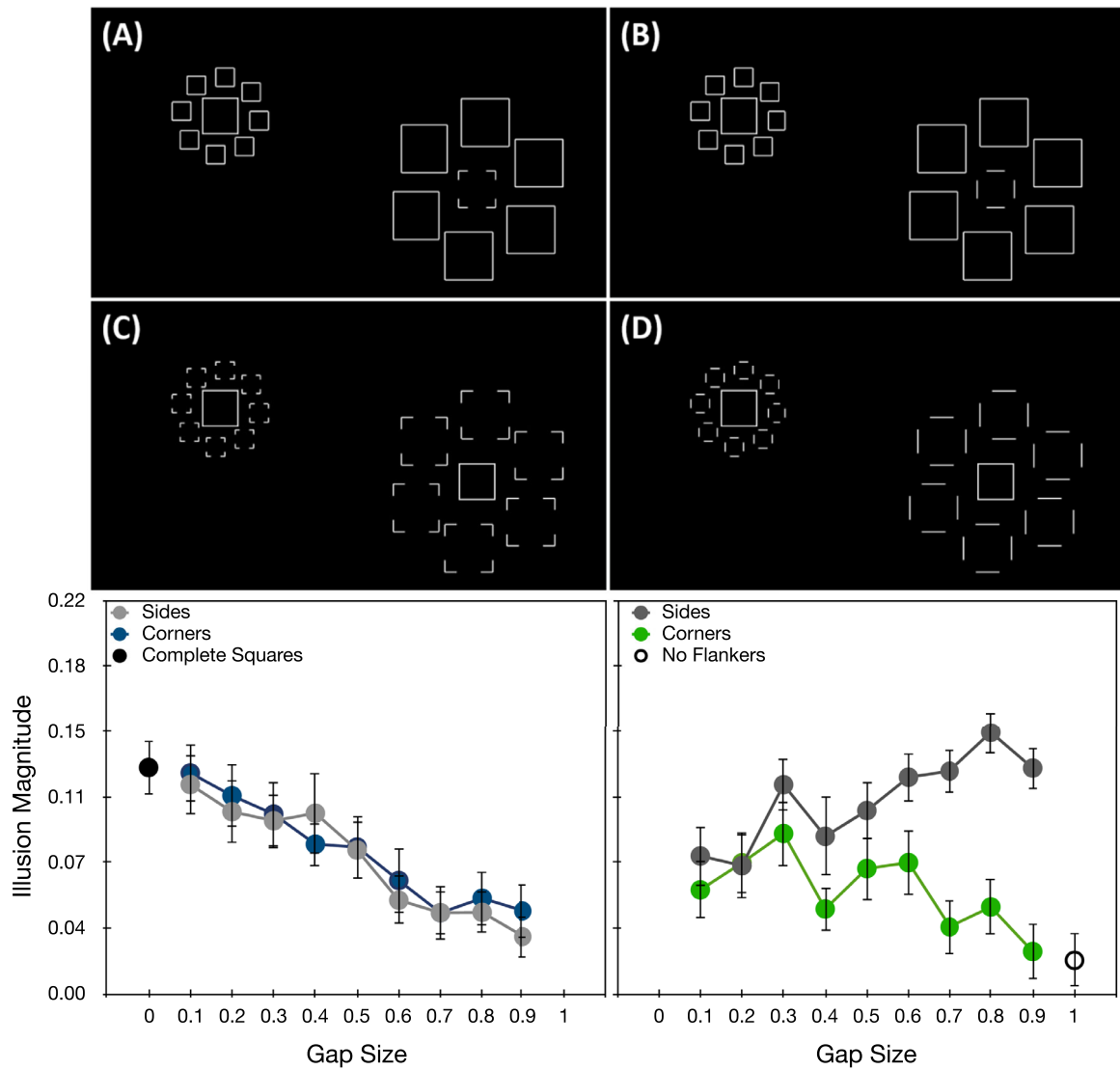


Figure 2. Top: examples of stimuli used in [Experiment 1](#). The reference configurations on the left present a reference target surrounded by smaller flankers. The test configuration on the right presents the adjustable test target surrounded by larger flankers. (A) Corners-target (i.e., a target composed of corners). (B) Sides-target (i.e., a target composed of sides). (C) Corners-flankers (i.e., flankers composed of corners). (D) Sides-flankers (i.e., flankers composed of sides). Gap size in these examples is 0.5. The reference target was always a complete square. Bottom: mean illusion magnitude for different element type conditions as a function of gap size for flankers (left) and targets (right) in [Experiment 1](#). Error bars indicate standard errors of the means.

formed by corners with 0.7 gap size). The size of the test target was adjusted by moving the computer mouse on the horizontal axis: a rightward movement increased the size and a leftward movement reduced it. The initial size of the test target was determined randomly at the beginning of each trial. The maximal size for adjusting the test target was 4° (on each side), to avoid any overlap with the surrounding flankers. To validate a trial, participants pressed the left button of the computer mouse. There was no time restriction, and no feedback was provided. Overall, there were 76 trials.

Subjective reports

After completing both blocks of the adjustment task, participants were asked to report their perception of the grouped target or flankers for each combination of part type and gap size. The displays were the ones containing gaps from the adjustment task (i.e., not including the ones without flankers or with complete squares only). In addition, the size of the targets in the two configurations of the display was identical. Participants indicated whether they perceived the elements of the grouped target or flankers as: (a) a

square, (b) another shape, or (c) unrelated elements, by pressing designated keys. Each display was evaluated once, resulting in a total of 36 trials.

Results and discussion

Adjustment task

Consecutive adjustments for each condition were averaged for each participant. Illusion magnitude was computed as a percentage of error in size adjustment compared to the reference target (i.e., adjusted target size minus reference size divided by reference size). The p -values were corrected with Greenhouse-Geisser epsilon in cases of sphericity violation. Illusion magnitude was subjected to a three-way repeated measures analysis of variance (ANOVA) with gap size, object role, and element type as within-subject factors, excluding the conditions with complete squares or no-flankers (Figure 2). The analysis revealed a main effect of gap size [$F(8, 72) = 5.06, p < 0.001, \eta_p^2 = 0.36$], showing decreased illusion magnitude with increasing gap size, and a main effect of element type [$F(1, 9) = 84.93, p < 0.001, \eta_p^2 = 0.90$], showing a higher magnitude for sides ($M = 0.09, SD = 0.6$) compared with corners ($M = 0.07, SD = 0.6$). The interaction between the two factors was significant [$F(8, 72) = 2.4, p < 0.02, \eta_p^2 = 0.21$], as were the interactions between object role and element type [$F(1, 9) = 40.82, p < 0.001, \eta_p^2 = 0.82$], object role and gap size [$F(8, 72) = 9.05, p < 0.001, \eta_p^2 = 0.50$], and among all three factors [$F(8, 72) = 2.8, p = 0.01, \eta_p^2 = 0.24$]. The main effect of object role did not reach significance [$F < 1$].

The data from the different object roles were further subjected to separate two-way repeated measures ANOVAs with gap size and element type as within-subject factors. For flankers as grouped squares, the analysis revealed a significant main effect of gap size, showing a decrease in magnitude with an increase in gap size [$F(8, 72) = 18.67, p < 0.001, \eta_p^2 = 0.68$]. The effect of element type and its interaction with gap size were not significant [$F(8, 72) = 2.58, p = 0.14, \eta_p^2 = 0.22; F < 1$, respectively]. For targets as grouped squares, the analysis revealed a significant main effect of element type [$F(1, 9) = 59.76, p < 0.001, \eta_p^2 = 0.87$], showing higher magnitude for sides-targets ($M = 0.11, SD = 0.6$) compared with corners-targets ($M = 0.6, SD = 0.6$), and an interaction between element type and gap size [$F(8, 72) = 3.53, p = 0.02, \eta_p^2 = 0.28$], showing a decrease in magnitude with an increase in gap size for corners-targets [$F(8, 72) = 2.75, p = 0.05, \eta_p^2 = 0.24$], and an increase in magnitude with an increase in gap size for sides-targets [$F(8, 72) = 2.53, p = 0.02, \eta_p^2 = 0.22$]. The effect of gap size did not reach significance [$F(8, 72) = 1.76, p = 0.1, \eta_p^2 = 0.16$].

Clearly, our objecthood manipulation affected the Ebbinghaus illusion, because for most conditions the illusion magnitude decreased with a decrease in visible contour. The odd case of sides-targets showing larger adjustment errors with decreasing amount of visible contour poses a challenge for the objecthood hypothesis at first glance, as it would be expected that the contextual effect would be in the same direction whether the grouped object is the target or the flankers. However, we believe it reflects a difficulty in comparing the degraded target to the reference rather than the influence of contextual objects. That is, integration of the target's contours to an imaginary square is impaired once the corners are removed, hence, the contours are integrated into an alternative shape, which is smaller in surface than the original square. Thus trying to match this smaller shape to the larger square will result in an adjustment bias regardless of the surrounding objects. Consequently, as the contour segments become smaller, the larger the difference between the alternative shape and the reference square will be. We find support for this idea in the results of the subjective reports portion of this experiment, described in the following section. In addition, an adjustment bias for the sides-target is confirmed in Experiment 3.

Subjective reports

Pearson's chi-squared tests were conducted on the distributions in the four different flankers and targets conditions (Figure 3). Reports were correlated with element type for flankers and targets [$\chi^2(2) = 29.9, p < 0.0001; \chi^2(2) = 63.48, p < 0.0001$, respectively]. That is, corners-targets were perceived as a square to a greater degree than sides-target (Figures 3A and 3B), and the same was true for corners-flankers versus sides-flankers (Figures 3C and 3D). In addition, reports were correlated with object role for sides but not for corners [$\chi^2(2) = 10.02, p < 0.01; \chi^2(2) = 0.71, p > 0.1$, respectively]. That is, corners-target and corners-flankers were perceived as squares to the same degree (Figures 3A and 3C), but sides-targets were perceived as a square less often than as another shape (38% and 54%, respectively; Figure 3B), whereas sides-flankers were perceived as squares more often than as another shape (57% and 31%, respectively; Figure 3D). Importantly, as clearly evident in the plots, the percentage of "square" reports decreased with increasing gap size, while the percentage of "other shape" reports increased, and the percentage of "unrelated elements" was higher for flankers than for targets formed by their sides (12% and 8%, respectively). Thus the results from the subjective reports are in line with previous findings on grouping and shape perception, showing that grouped corners lead to a better perception of a square compared with side elements (e.g., Hadad & Kimchi, 2008). However, they do not correspond to the results of the adjustment

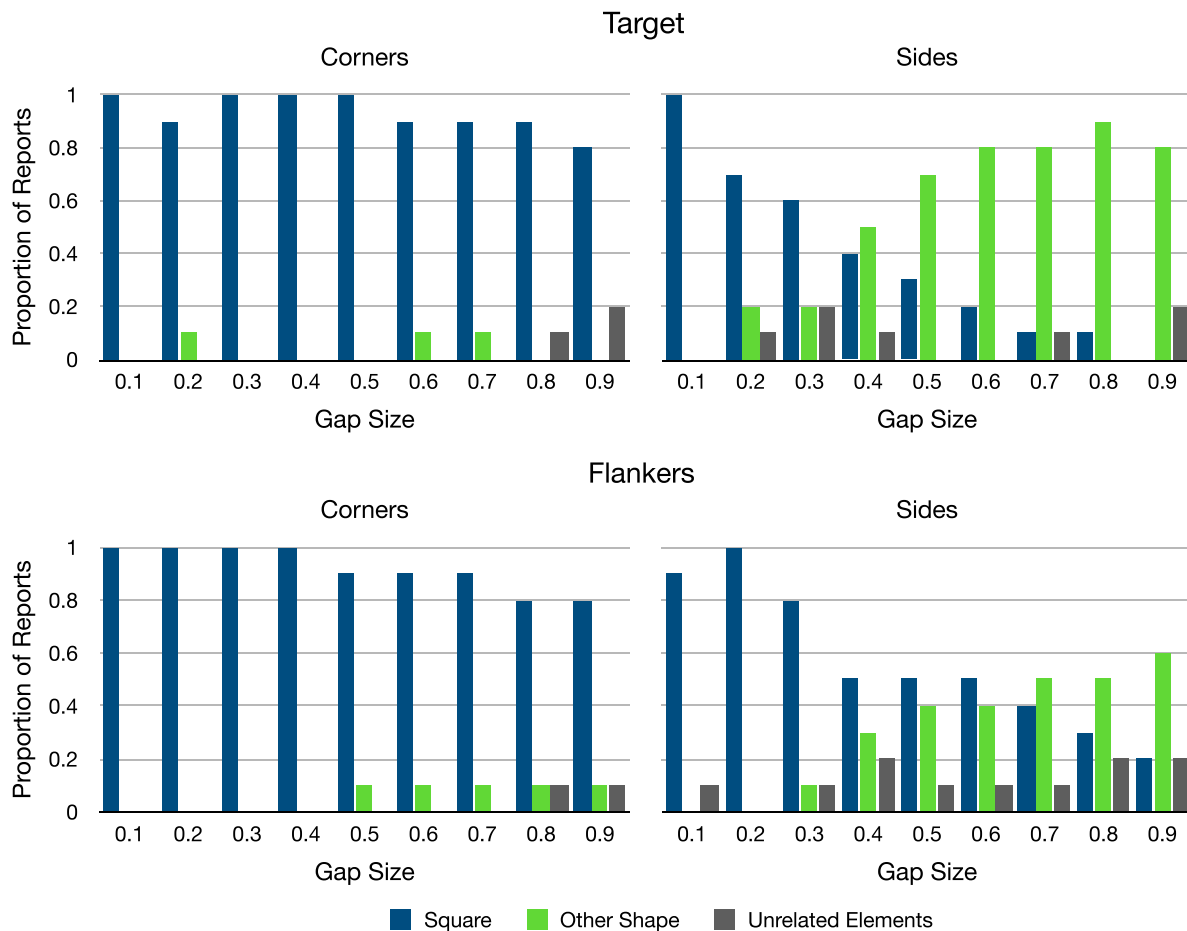


Figure 3. Proportion of reports at each gap size in the different object role and element type conditions in [Experiment 1](#).

task. This discrepancy suggests the Ebbinghaus illusion is not affected directly by the perceived shape of the objects in the configuration. [Experiment 2](#) was designed to explore this question further.

Experiment 2

The lack of compatibility between subjective reports and the contextual effect found in [Experiment 1](#) raises an important question, because it was previously suggested that the magnitude of the illusion depends on similarity between the target and its surrounding flankers (e.g., [Choplin & Medin, 1999](#); [Coren & Enns, 1993](#); [Coren & Miller, 1974](#); [Vuk & Podlesek, 2005](#)). [Coren and Miller \(1974\)](#), for example, demonstrated a correlation between illusion magnitude and similarity ratings, showing a weaker illusion with decreasing similarity. Later, [Vuk and Podlesek \(2005\)](#) suggested that the flankers' effects depend on their configuration as a whole rather than their global shape. That is, the combination of elements constructing the target and flankers could be more important than their outlines. This issue is pertinent to our study because the subjective reports

in [Experiment 1](#) indicate that sides-flankers resemble squares less than corners-flankers, thus creating a difference in their global shape with the gap-size manipulation. Still, it is possible that the two types of incomplete square flankers were equally dissimilar to the target, which was a complete square, resulting in a similar effect on illusion magnitude. To examine this possibility, in [Experiment 2](#) we varied the degree of similarity between target and flankers by presenting incomplete targets with incomplete flankers in every possible combination of element type. For example, a corners-target surrounded by corners-flankers should have greater similarity than a corners-target surrounded by sides-flankers. If configural similarity is a factor in the objecthood effect, we expected to find a higher illusion magnitude when the target and flankers were composed of the same elements compared with when they were composed from different elements. The gap size of the target was fixed at 0.5 in this experiment. Due to the difference in illusion magnitudes observed in [Experiment 1](#) for the two target types with this gap size we expected an effect in [Experiment 2](#) as well, showing higher adjustment error for the sides-target.

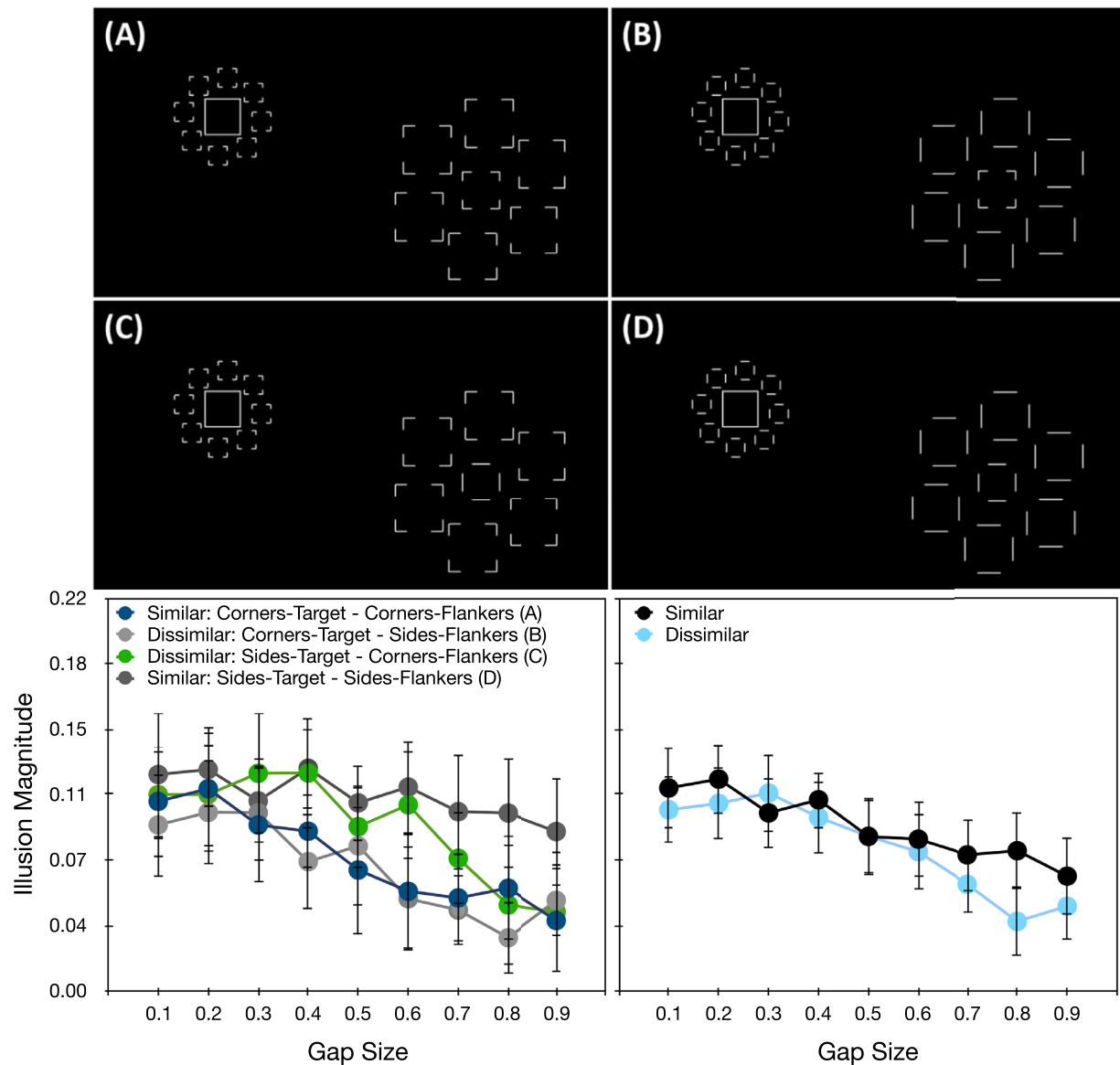


Figure 4. Top: examples of stimuli used in [Experiment 2](#). (A) Similar: corners-target and corners-flankers. (B) Dissimilar: corners-target and sides-flankers. (C) Dissimilar: sides-target and corners-flankers. (D) Similar: sides-target and sides-flankers. Gap size is 0.5 in these examples. The reference target was always a complete square. Bottom: mean illusion magnitude for different target and similarity conditions as a function of flankers' gap size (left), and main effect of similarity (right) in [Experiment 2](#). Error bars indicate standard errors of the means.

Method

Participants

Ten naïve students, new to the study, from the École Polytechnique Fédérale de Lausanne (EPFL) participated in this experiment (three females; mean age: 21.40 years; range: 19–24 years). Participants signed informed consent forms and were paid for their participation. Procedures were conducted in accordance with the Declaration of Helsinki (except for preregistration) and were approved by the local ethics committee.

Apparatus, stimuli, and procedure

[Experiment 2](#) was identical to [Experiment 1](#) except for the following: the test target and flankers were all incomplete objects. Target and flankers' element types were manipulated independently in separate blocks, creating two similarity conditions. That is, a corners-target was surrounded by corners-flankers (i.e., similar, [Figure 4A](#)), or sides-flankers (i.e., dissimilar, [Figure 4B](#)), and a sides-target was surrounded by corners-flankers (i.e., dissimilar, [Figure 4C](#)) or sides-flankers (i.e., similar, [Figure 4D](#)). Only the flankers were subjected to the gap size manipulation.

The gap size of the test target was fixed at 0.5. The four conditions were presented randomly, each composed of 18 adjustments (9 gap sizes \times 2 adjustments trials). Example stimuli in [Experiment 2](#) with minimum (0.1) and maximum (0.9) gap size can be found in the Supplementary File (Supplementary Figure S2).

Results and discussion

Illusion magnitude was subjected to a three-way repeated measures ANOVA with gap size, target element type, and similarity as within-subject factor. The analysis revealed a significant main effect of gap size [$F(8, 72) = 11.98, p < 0.001, \eta_p^2 = 0.57$], showing a decrease in illusion magnitude with increasing gap size, a significant main effect of target element type [$F(1, 9) = 7.34, p = 0.02, \eta_p^2 = 0.45$], showing stronger illusion for sides-target ($M = 0.1, SD = 0.09$) compared with corners-target ($M = 0.07, SD = 0.09$). The effect of similarity was only marginally significant [$F(1, 9) = 3.82, p = 0.08, \eta_p^2 = 0.30$], showing stronger illusion for similar ($M = 0.09, SD = 0.09$) compared with dissimilar ($M = 0.08, SD = 0.09$) target and flankers' element type. This trend seems to come from some differences between similar and dissimilar condition at the largest gap sizes. None of the other effects reached significance ($p > 0.23$). The plots at the bottom of [Figure 4](#) depicts the illusion magnitude in each of the four conditions (left), and for the similarity conditions, for convenience (right).

The results of [Experiment 2](#) give further support to the hypothesis that objecthood affects the Ebbinghaus illusion, as a decrease in illusion magnitude was found with increasing gap size. The higher magnitude shown with sides-target compared with corners-target is in accordance with the results of [Experiment 1](#), suggesting that this type of target is more fragile. The effect of similarity was only marginally significant, showing no difference between conditions for most of the gap sizes. This result suggests that similarity in configuration between target and flankers has little to do with the illusion magnitude, at least in the displays used in this experiment.

Experiment 3

In contrast to previous studies, our results so far point to shape having no role in the Ebbinghaus illusion. To examine this hypothesis further, in [Experiment 3](#) we tested the effect of similarity in global shape between target and flankers by presenting a square target surrounded by cross-like flankers. Similar to the square flankers in the previous experiments, the cross flankers were constructed from straight lines or corners elements. Flankers' element type was manipulated to keep the experimental conditions as similar as possible

to those of [Experiments 1](#) and [2](#). We did not expect this factor to have an effect on the illusion, as the different types of elements did not convey different shape information when constructing the crosses in our displays. On the other hand, a cross shape is considerably different from that of a square. Hence, if similarity in shape plays a role, illusion magnitude should be weaker for dissimilar flankers. That is, illusion magnitude should be lower in this experiment compared with the previous experiment.

As in [Experiment 1](#), we collected subjective reports to get a more comprehensive account of objecthood and shape perception for the stimuli employed in our displays. Since reports of the square targets were already collected in [Experiment 1](#), in this experiment we collected reports only regarding the cross-like flankers.

Method

Participants

Ten naïve students, new to the study, from the École Polytechnique Fédérale de Lausanne (EPFL) participated in this experiment (three females; mean age: 23.40 years; range: 20–26 years). Participants signed informed consent forms and were paid for their participation. Procedures were conducted in accordance with the Declaration of Helsinki (except for preregistration) and were approved by the local ethics committee.

Apparatus, stimuli, and procedure

Adjustment task

[Experiment 3](#) was identical to [Experiment 2](#) except for the following: the test target was an incomplete square and the flankers were crosses. Crosses were constructed from corners segments oriented outwards—“*corners-flankers*” ([Figures 5A](#) and [5C](#)) or line segments positioned to form the crosses' arms—“*arms-flankers*” ([Figures 5B](#) and [5D](#)). Target and flankers' element types were manipulated independently. Only the flankers were subjected to the gap size manipulation, whereas the gap size of the test target was fixed at 0.5. A baseline condition with complete crosses (i.e., gap size 0) was included as well. There were 76 trials in total. Example stimuli in [Experiment 3](#) with minimum (0.1) and maximum (0.9) gap size can be found in the Supplementary File (Supplementary Figure S3).

Subjective reports

After completing the adjustment task, participants were asked to indicate whether they perceived the elements of the grouped flankers as: (a) a square, (b) a cross, (c) another shape, or (d) unrelated elements, for each gap size.

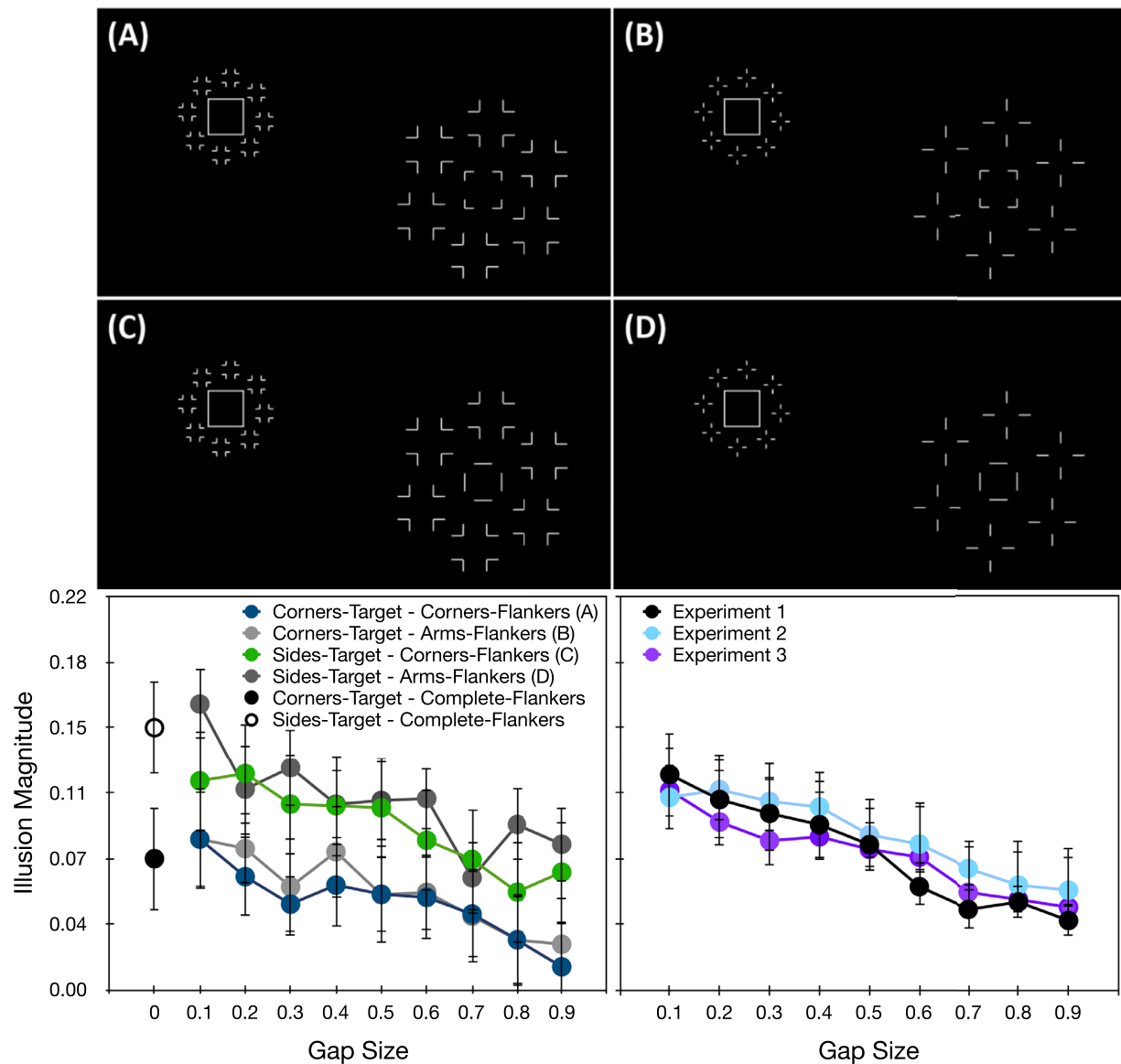


Figure 5. Top: examples of stimuli used in [Experiment 3](#). Targets were squares flanked by crosses. (A) Corners-target and corners-flankers. (B) Corners-target and arms-flankers. (C) Sides-target and corners-flankers. (D) Sides-target and arms-flankers. Gap size is 0.5 in these examples. The reference target was always a complete square. Bottom: mean illusion magnitude for different target and flankers part type conditions as a function of gap size in [Experiment 3](#) (left), and gap-size effect in all three experiments (right). Error bars indicate standard errors of the means.

Results and discussion

Adjustment task

Illusion magnitude was subjected to a three-way repeated measures ANOVA with gap size, target element type, and flankers' element type as within-subject factor. The analysis revealed a significant main effect of gap size [$F(8, 72) = 10.12, p < 0.001, \eta_p^2 = 0.53$], showing a decrease in illusion magnitude with increasing gap size, and a main effect of target element type [$F(1, 9) = 12.85, p = 0.006, \eta_p^2 = 0.59$], showing a higher magnitude for sides-target ($M = 0.1, SD =$

0.08) compared with corners-target ($M = 0.05, SD = 0.07$). The effect of flanker element type did not reach significance [$F(8, 72) = 2.04, p = 0.19, \eta_p^2 = 0.19$], nor did any of the interactions [$F_s < 1$]. Thus, similar to the results of the previous experiments, [Experiment 3](#) showed a reduction in illusion magnitude with decreased objecthood of the flankers ([Figure 5](#)).

To test whether the illusion is affected by shape similarity between target and flankers, we compared illusion magnitudes in [Experiments 2](#) and [3](#). We conducted a mixed-design repeated measures ANOVA with gap size as within-subject factor and experiment as between-subjects factor. The analysis revealed a

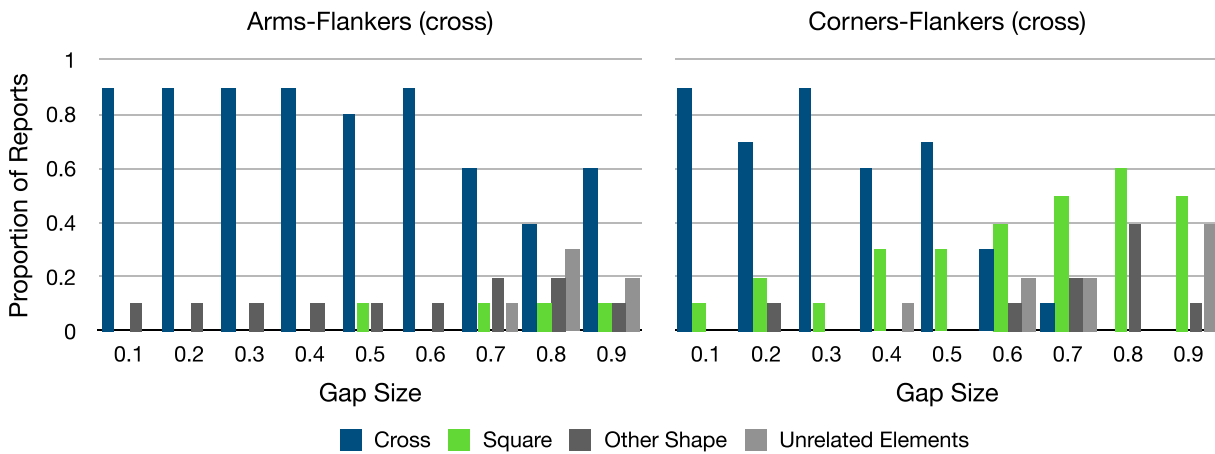


Figure 6. Proportion of reports at each gap size in the different element type conditions in Experiment 3.

significant main effect of gap size [$F(8, 144) = 21.28$, $p < 0.001$, $\eta_p^2 = 0.54$], showing decreasing magnitude with increasing gap size. The main effect of experiment was not significant, as was the interaction between experiment and gap-size [$F_s < 1$]. Thus the comparison between Experiments 2 and 3 shows that the objecthood effect was similar across the different shape similarity manipulations (Figure 5). Thus similarity of shape between target and flankers, global or configurational, does not seem to contribute to the objecthood effect on the illusion.

Subjective reports

Pearson's chi-squared tests were conducted on the distribution of reports from the two flankers' conditions (Figure 6). It was found that reports were correlated with flankers' element type [$\chi^2(3) = 27.25$, $p < 0.0001$]. Specifically, arms-flankers were perceived as crosses in 77% of the trials, as squares in 4%, as another shape in 12%, and as unrelated elements in 7%. On the other hand, corners-flankers were perceived as crosses in 47% of the trials, as squares in 33%, as another shape in 10%, and as unrelated elements in 10%. As clearly evident in the plots, the percentage of "cross" reports decreased with increasing gap size, whereas the percentage of the alternative reports increased, and this trend was more pronounced for corners-flankers compared with arms-flankers. As in Experiment 1, the subjective reports did not match the results of the adjustment task, suggesting that perceived shape does not contribute to the illusion.

Adjustment bias

Similar to Experiments 1 and 2, a main effect of target element type was found. Also, in the baseline conditions, where flankers were complete crosses, a significantly higher illusion magnitude was found for

sides-target ($M = 0.15$, $SD = 0.09$) compared with corners-target ($M = 0.07$, $SD = 0.08$), ($t = 2.91$, $p = 0.02$, two-tailed). This pattern suggests an adjustment bias. To test this possibility, we conducted a control experiment in which 10 new participants (three females; mean age: 21.30 years; range: 19–25 years) were presented with displays containing test and reference targets but no flankers. They were asked to perform the adjustment task, comparing a test target that was either a full square, a square made of corners, a square made of sides, or a cross made of corners to a complete square as a reference target. These grouped targets were presented for two trials each in a random order. The results of this control experiment revealed that illusion magnitude was significantly different from zero for target-sides ($M = 0.07$, $SD = 0.09$, $t = 2.41$, $p = 0.04$, two-tailed), but not for the others ($t \leq 1$). This result matches the difference between the two target types in our experiments, supporting also the idea that a bias in adjustment was underlying the odd results in the sides-target condition in Experiment 1.

Experiment 4

The gap-size effect found in Experiments 1 to 3 supports the hypothesis that the Ebbinghaus illusion is sensitive to the quality of the objects in the comparison. However, it is possible that the gap-size manipulation introduced another factor that contributed to the effect. Specifically, reducing the same proportion of contour from small and large flankers left different amounts of visible contours in each configuration, because the amount of contour for the targets was fixed. As in our paradigm it is not possible to disentangle the effect of small flankers from that of the large flankers on illusion magnitude, it is possible that the varying ratio in amount of visible contour led to the gap-size

effect. In this case a low-level contour interaction could explain the effect. To rule out this possibility, in [Experiment 4](#) we manipulated objecthood in a way that kept both ratio and amount of visible contour constant in both configurations—instead of disrupting the objects by discarding parts of their contour, we introduced a rotation manipulation to the elements forming the objects. We hypothesized that the illusion magnitude would decrease with increasing rotation angle, because of reduced objecthood of the flankers. Subjective reports were collected as well to account for the perceived shape of the flankers with rotated parts.

Methods

Participants

Ten naïve students, new to the study, from the École Polytechnique Fédérale de Lausanne (EPFL) participated in this experiment (four females; mean age: 22 years; range: 18–25 years). Participants signed informed consent forms and were paid for their participation. Procedures were conducted in accordance with the Declaration of Helsinki (except for preregistration) and were approved by the local ethics committee.

Apparatus, stimuli, and procedure

Adjustment task

[Experiment 4](#) was identical to the previous experiments except for the following: the test target was always a complete square and the flankers were four-element objects constructed of corners with a 0.5 gap size. The corners were rotated in two opposite directions (i.e., outward rotation; [Figure 7A](#)), or in the same direction (i.e., clockwise rotation; [Figure 7B](#)). Rotation angle was between 5° and 40° in steps of 5°. This range was chosen to make sure that no incidental collinearity grouping occurred between pairs of rotated elements while allowing a similar number of trials per condition as in the previous experiments. A baseline condition, where the corners were not rotated (i.e., similar to the stimuli in the previous experiments) was included as well. There were 34 trials in total. Example stimuli in [Experiment 4](#) with minimum (5°) and maximum (40°) rotation angle can be found in the Supplementary File (Supplementary Figure S4).

Subjective reports

After completing the adjustment task, participants were asked to indicate whether they perceived the elements of the grouped flankers as: (a) a square, (b)

another shape, or (c) unrelated elements, for each rotation angle.

Results and discussion

Adjustment task

Illusion magnitude was subjected to a two-way repeated measures ANOVA with degree of rotation and flankers' part rotation direction as within-subject factor. The analysis revealed a significant main effect of degree of rotation [$F(7, 63) = 6.25, p < 0.001, \eta_p^2 = 0.41$], showing a decrease in illusion magnitude with increasing rotation angle. There was no significant effect of rotation direction, nor an interaction between the two factors [$F_s < 1$]. Thus, similar to the results of the previous experiments, [Experiment 4](#) showed a reduction in illusion magnitude with decreased objecthood of the flankers ([Figure 7](#)).

Subjective reports

Pearson's chi-squared tests were conducted on the distribution of reports from the two flankers' conditions ([Figure 8](#)). It was found that reports were correlated with flankers' part rotation direction [$\chi^2(2) = 6.01, p < 0.04$]. Specifically, when the parts were rotated clockwise, the objects were perceived as squares in 36% of the trials, as another shape in 36%, and as unrelated elements in 18%. On the other hand, when the parts were rotated outward, the objects were perceived as squares in 21% of the trials, as another shape in 21%, and as unrelated elements in 29%. As clearly evident in the plots, the percentage of "square" reports decreased with increasing rotation angle, while the percentage of the alternative reports increased, and this trend was more pronounced with outward rotation compared with clockwise rotation. As in [Experiments 1](#) and [3](#), the subjective reports do not seem to reflect a factor that affects the adjustment task, suggesting that perceived shape does not contribute to the illusion.

General discussion

The main goal of this study was to examine whether objecthood has a role in the Ebbinghaus illusion. The results of our experiments demonstrate that degrading the quality of an object by means of grouping strength between the elements constructing the object affects size estimation. In line with our hypothesis, we found that reduced grouping strength led to a weaker illusion. Specifically, increasing the gap size ([Experiments 1–3](#)), or rotation angle ([Experiment 4](#)) between the objects' elements resulted in a decreased illusion

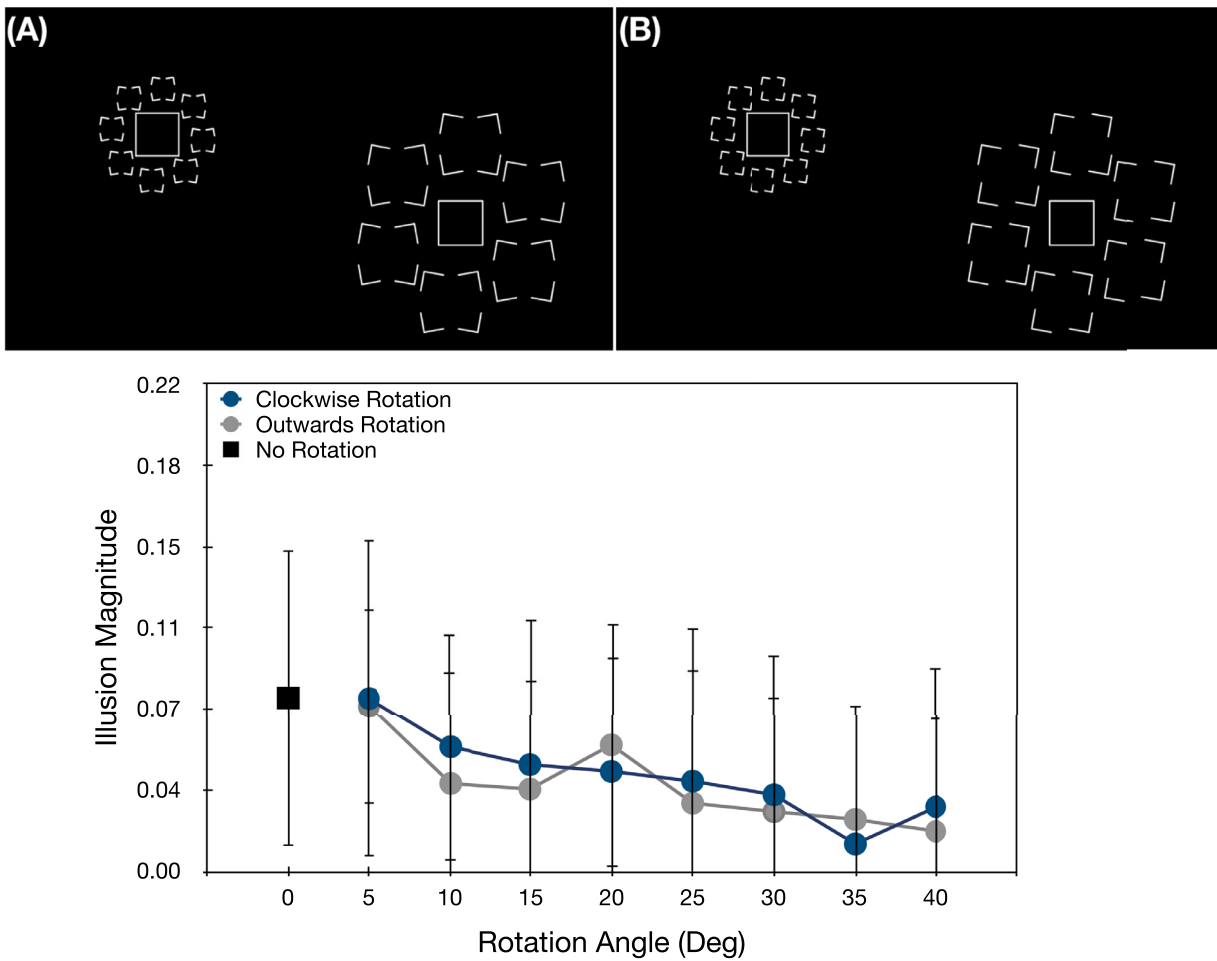


Figure 7. Top: examples of stimuli employed in Experiment 4. Test and reference targets were complete squares. Flankers were made of (A) corners rotated outwards (i.e., opposite directions), or (B) clockwise (i.e., same direction). Rotation is 10° in these examples. Bottom: mean illusion magnitude for different flankers' part rotation direction conditions as a function of degree of rotation in Experiment 4. Error bars indicate standard errors of the means.

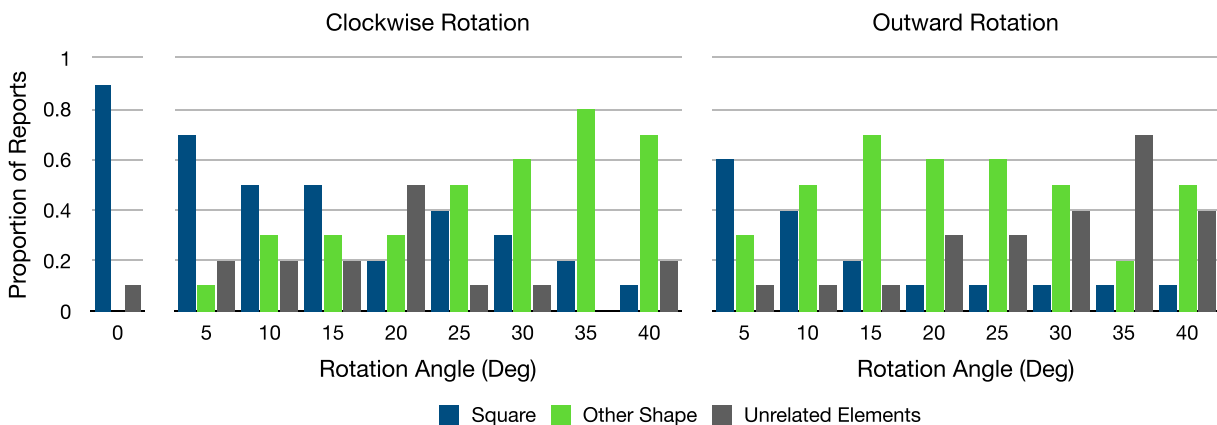


Figure 8. Proportion of reports at each rotation angle in the different rotation direction conditions in Experiment 4.

magnitude. This result is consistent with the size contrast account, which posits that the illusion is a product of a comparative mechanism rather than low-level contour interactions. This is because as the objecthood of the flankers or target was reduced, the less effective they were in the comparison. The contour interaction account is less likely to explain our results because the ratio between close and far contours of the flankers relative to the target was fixed during the objecthood manipulation. If the target was subjected to attraction and repulsion from the flankers, illusion magnitude should have been the same for all gap sizes and rotation angles. [Experiment 4](#) challenged also an alternative explanation that the objecthood effect found in [Experiments 1–3](#) was due to a difference in contour ratio between target and flankers in the test and reference, as this ratio was kept constant in this experiment. It is important to note, however, that the contour interaction account is not developed enough to provide clear predictions ([Todorović and Jovanović, 2018](#)). It is possible that close and far contours are weighted differently depending on some attribute of the flankers, or that the point of reference for far-close contour ratio is other than the center of the object (e.g., the distance between nearest points of flankers and targets). However, our finding of a similar effect with two different manipulations of the visible contours surrounding the target cannot be parsimoniously accommodated by the alternative account. Thus we suggest that our results provide evidence of the role of mid-level processes in the illusion, supporting the size contrast account.

Another objective of this study was to address the question of the role of shape similarity in the illusion, as previous studies showed conflicting results ([Choplin & Medin, 1999](#); [Coren & Miller, 1974](#); [Vuk & Podlesek, 2005](#)). Importantly, we found no evidence for configural similarity, because there was no difference in illusion magnitude, nor in the objecthood effect (i.e., the effect of gap size on illusion magnitude), when target and flankers were composed of similar or different element configurations ([Experiment 2](#)), or when they had the same or different global shapes ([Experiments 2 and 3](#), respectively). Furthermore, measuring the perceived shapes of the objects in our displays show no correspondence with the size error measure of the illusion. That is, the gap size manipulation reduced the perceived “squareness” (or “cross-ness”) of the flankers, but this effect differed for the two element types used to construct them, which was a factor that did not affect the illusion magnitude. The latter may indicate a dissociation between mechanisms involved in phenomenology (e.g., subjective reports) and in visuo-motor integration (e.g., adjustment task). For example, [Aglioti, DeSouza, and Goodale \(1995\)](#) demonstrated a dissociation between perception and action towards an Ebbinghaus display; as the

illusion was obtained with perceptual judgements, however, grasping the test target was not affected by the surrounding stimuli. A dissociation between direct and indirect measures of perceptual organization has been reported by [Schmidt and Schmidt \(2013\)](#), who demonstrated that grouping strength of different grouping rules (e.g., similarity by shape and similarity by brightness) did not correlate with priming effects of those rules. Hence, we propose that the objecthood effects reported here and shape similarity effects in previous studies of the Ebbinghaus illusion reflect an effect of figural “goodness” ([van der Helm, 2014](#); for a comprehensive review on Gestalt factors in visual perception see [Peterson & Kimchi, 2013](#); [Wagemans et al., 2012](#)). Support to this hypothesis may be found in a study by [Rose and Bressan \(2002\)](#), who showed that even when the target and flankers’ shapes were identical, the magnitude of the illusion varied for different shapes. Because some shapes are better than others, their “goodness” could have caused the variations in illusion magnitudes. This is a speculation at this point, since “goodness” was not measured in that study, but it poses an interesting question that merits further investigation.

Interestingly, the adjustment bias we found for sides-target suggests that shape information is crucial for the adjustment procedure. When the test target contains less shape related information, there is difficulty completing it into an imaginary square that is comparable with the reference square. As suggested by the subjective reports, the visible segments can be completed into another shape, for example an octagon, which has a smaller surface. Thus, the size of this shape would result in an adjustment bias to equal that of the square regardless of the surrounding objects. The effect found in [Experiment 1](#) for the sides-target is compatible with this idea: the surface of the target became smaller with a decrease in visible contour, leading to a larger adjustment error with each increment in gap size. This pattern is not evident with the corners-target, because corners convey more shape information (e.g., [Hadad & Kimchi, 2008](#); [Persike & Meinhardt, 2017](#); [Poirier & Wilson, 2007](#)), thus, providing a target that is a comparable square to the reference.

Our results accord with a recent study by [Lavrenteva and Murakami \(2018\)](#). In their study, the target and flankers were defined by first- and second-order attributes (e.g., luminance and local contrast, respectively). Interestingly, an asymmetry in the size estimation error was found, showing that first-order flankers had the same effect on size estimation with all target types, whereas second-order flankers affected first-order targets less than second-order targets. The authors proposed that this asymmetry resulted from different weights given to first- and second-order attributes when target and flankers differed in the sensory evidence they provided. The objecthood effect

found in the current study can be another example of changing weights. That is, a degraded object weighs less than a good object since it contains less coherent information, and thus, it has less of an effect in the size contrast process.

Lastly, it is important to acknowledge that the size contrast account has its own shortcoming, specifically, it being more of a description of the phenomenon rather than an explanation (Todorović and Jovanović, 2018). However, the size contrast account poses that object-level representations are compared. Thus the degree of objecthood would be crucially influencing the process, as the object as a whole is compared, whether it has a complete or grouped outline. A few results from previous studies (e.g., Weintraub & Schneck, 1986) showing the illusion with only dots or lines as flankers are not easily explained with just objecthood. Hence, an interesting line of future research would examine other processes of perceptual organization, such as grouping and segmentation of the target and flankers, which may be involved in such complex displays of the illusion in addition to size contrast, contour interactions and their potential interactions.

Conclusion

Objecthood plays a role in the size adjustment error demonstrated in the Ebbinghaus illusion. The current study provides support for a higher-level size contrast mechanism underlying the illusion and proposes that better objects carry more weight during the comparison process. This opens a new avenue of studying objecthood through visual illusions.

Keywords: objecthood, grouping, size illusion

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Commercial relationships: none.
Corresponding author: Einat Rashal.
Email: einatrashal@gmail.com.
Address: École Polytechnique Fédérale de Lausanne (EPFL), Brain Mind Institute, Laboratory of Psychophysics, Station 19, 1015 Lausanne, Switzerland.

Footnote

¹We consider the center of the flankers to be the relative point from which attraction and repulsion are operating by close and far contours, respectively. Although this has not been made explicit in previous studies, this seems to be the underlying assumption. Theoretically, attraction and repulsion may operate within another function, however, it is not clear what it might be (e.g., Todorovic and Jovanovic, 2018).

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