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Interobject grouping facilitates visual awareness

Timo Stein
Center for Mind/Brain Sciences, University of Trento, Rovereto, Italy

Daniel Kaiser
Center for Mind/Brain Sciences, University of Trento, Rovereto, Italy

Marius V. Peelen
Center for Mind/Brain Sciences, University of Trento, Rovereto, Italy

In organizing perception, the human visual system takes advantage of regularities in the visual input to perceptually group related image elements. Simple stimuli that can be perceptually grouped based on physical regularities, for example by forming an illusory contour, have a competitive advantage in entering visual awareness. Here, we show that regularities that arise from the relative positioning of complex, meaningful objects in the visual environment also modulate visual awareness. Using continuous flash suppression, we found that pairs of objects that were positioned according to real-world spatial regularities (e.g., a lamp above a table) accessed awareness more quickly than the same object pairs shown in irregular configurations (e.g., a table above a lamp). This advantage was specific to upright stimuli and abolished by stimulus inversion, meaning that it did not reflect physical stimulus confounds or the grouping of simple image elements. Thus, knowledge of the spatial configuration of objects in the environment shapes the contents of conscious perception.

Introduction

Although visual scenes generate a complex, ambiguous mosaic of light on the retina, we have a stable, coherent conscious perception of our visual environment composed of objects, parts of objects, and groups of objects (Palmer, 1999). In organizing visual perception the visual system takes advantage of regularities in the visual input to group related image elements into higher-order perceptual units. Principles of such perceptual grouping determine the part-whole hierarchy among objects in a visual scene, thereby shaping conscious perception and contributing to the efficiency of visual processing (Wagemans et al., 2012). Most work on perceptual grouping has been carried out in the tradition of Gestalt psychology, investigating how physical regularities among simple stimuli such as dots, lines, or simple shapes influence visual perception.

However, our visual environment is not only structured by such physical regularities among simple image elements but also contains regularities among more complex, meaningful stimuli at more conceptual levels. For example, objects in real-world scenes do not appear at random locations, but are typically experienced at regular, predictable positions relative to each other (Bar, 2004): Lamps usually appear above not below tables. Recent evidence indicates that the visual system does extract such real-world spatial regularities among meaningful stimuli to perceptually group complex, natural objects we typically encounter in our everyday environments (Gronau & Schachar, 2014; Kaiser, Stein, & Peelen, 2014; Riddoch, Humphreys, Edwards, Baker, & Wilson, 2003). Grouping based on this prior knowledge of the typical spatial configurations of objects can improve object identification, short-term memory, and long-term memory retrieval (Kaiser, Stein, & Peelen, 2015; Roberts & Humphreys, 2011; Tobon, Gronau, Scheuplein, Mecklinger, & Levy, 2014). These initial findings raise the intriguing possibility that grouping of complex, meaningful objects enhances the efficiency of visual processing, in a way analogous to the well-established effects of Gestalt-like grouping among simple stimuli. Indeed, object grouping according to real-world spatial regularities is reflected in reduced attentional competition (Kaiser et al., 2014), similar to reduced attentional competition for Gestalt-like grouping based on cues such as illusory contours (McMains & Kastner, 2011). Interestingly, physical regularities in the visual input can also determine whether we consciously perceive a stimulus in the first place. Recently, it has been found

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that simple stimuli that can be grouped by forming an illusory contour are prioritized for access to conscious awareness (Wang, Weng, & He, 2012).

In the present study, we asked whether the grouping of natural, meaningful objects according to real-world regularities has a similar impact on the contents of conscious perception. To address this question, we tested whether grouping among complex objects can occur before these objects become available for conscious access and hence determine which objects gain access to conscious awareness. Visual awareness is thought to reflect the transient dominance of neural assemblies representing the conscious percept over competing assemblies representing other aspects of the visual input (Koch, 2004). These competitive dynamics can be tracked using continuous flash suppression (CFS), in which high-contrast patterns flashed into one eye can suppress conscious perception of stimuli presented to the other eye for several seconds (Tsuchiya & Koch, 2005). By tracking the duration of perceptual suppression under CFS for different stimuli, the *breaking CFS* paradigm (b-CFS; Stein, Hebart, & Sterzer, 2011) allows a direct comparison of the potency of different stimuli to gain access to awareness (e.g., Gayet, Van der Stigchel, & Paffen, 2014; Jiang, Costello, & He, 2007; Wang et al., 2012).

Adopting a b-CFS paradigm, we compared suppression durations for object pairs presented in their typical, regular configuration with an irregular condition where the position of the individual objects was interchanged, thus disrupting regularity (see Figure 1a). If objects that can be grouped based on real-world regularities had a competitive advantage in gaining access to awareness, regularly positioned object pairs should break suppression more quickly than irregularly positioned pairs.

Experiment 1

Experiment 1 tested whether suppression durations would be shorter for regular than for irregular object pairs. Although regular and irregular pairs consisted of identical single objects with identical pixel values that only differed in their spatial configuration within the pairs, differences in breaking CFS could in principle be related to differences in the configuration of simple image elements between regular and irregular pairs (e.g., differences in Gestalt-like properties such as parallelism or symmetry). To control for such potential differences, we included a condition in which all pairs were inverted, i.e., rotated by 180°. Inversion disrupts the typical configuration of the pairs, while preserving all potential differences related to the grouping of simple image elements. Thus, inversion should abolish any genuine effect of real-world regularities.

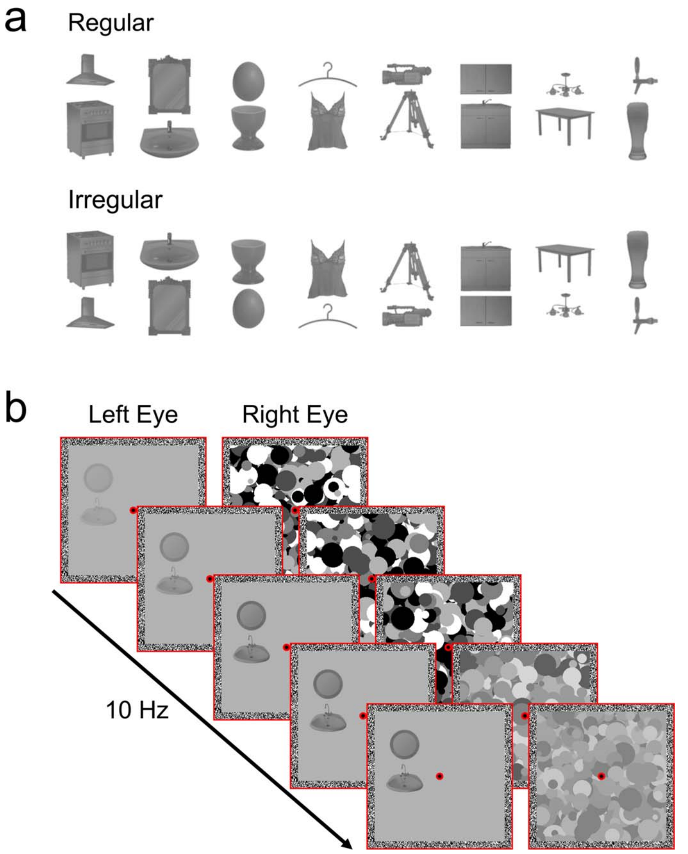

Figure 1. Stimuli and procedure. (a) Examples of upright regular (top row) and upright irregular (bottom row) object pairs. Regular and irregular pairs consisted of the same individual everyday objects. For the regular pairs, these objects were arranged according to their typical real-world configuration. For the irregular pairs, the positions of the individual objects were interchanged. (b) Schematic of an example trial. To induce interocular suppression, CFS masks flashing at 10 Hz were presented to one eye, while a target stimulus was gradually introduced to the other eye. Participants indicated on which side of fixation the target stimulus or any part of the target stimulus became visible. The contrast of the target stimulus increased over the first second of a trial, while the contrast of the CFS masks was slowly ramped down over the course of a trial.

Method

Participants

In Experiment 1 we explored the possibility that interobject positional regularities influence suppression durations for upright pairs but not for inverted pairs. For this first exploratory experiment we decided to test a relatively small sample size of $N = 14$. All 14 volunteers (all female, age range 18–36 years, mean 23.6 years) recruited through the University of Trento subject pool participated for course credit or payment. All participants gave informed written consent, reported normal or corrected-to-normal vision, and were naïve as to the purpose of the experiment. The study protocol was approved by the ethical committee of the University of Trento and was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki.

Apparatus and stimuli

Observers viewed a 19-in. CRT monitor (1280 × 1024 pixels resolution, 100 Hz refresh rate) dichoptically through a custom-built mirror stereoscope. The observer's head was stabilized by a chin-and-head rest at a viewing distance of approximately 50 cm. The mirrors of the stereoscope were adjusted for each observer to promote stable binocular fusion. The screen was black except for the uniform light-gray area in which the stimuli were presented. Two red frames (10.4° × 10.4°) were displayed side-by-side on the screen such that one frame was shown to each eye (distance between the centers of the two frames 22.0°). To further support binocular fusion, noise contours (width 0.5°) consisting of random pixels were presented within the red frames. In the center of each frame a red fixation dot (0.5° × 0.5°) with a black dot (0.2° × 0.2°) in its center was displayed. Participants were asked to maintain stable fixation throughout the experiment. Visual stimuli were presented with Matlab (The MathWorks, Natick, MA) using the Cogent 2000 toolbox functions (www.vislab.ucl.ac.uk/cogent.php).

Target stimuli were 12 pairs of everyday-objects with a typical spatial configuration in the vertical direction, for example a lamp above a dining table, a bathroom mirror above a bathroom sink, or a TV screen above a DVD player. In the "regular" condition, these pairs were presented in their typical configuration (e.g., lamp above a dining table), whereas in the "irregular" condition all pairs were presented with individual object positions interchanged (e.g., lamp below a dining table; Figure 1a). For each single object pair, there were two different exemplars, resulting in a set of 24 object pairs (size 1.6°–2.8° × 2.8°–5.0°) per condition. Inverted versions of these regular and irregular pairs were created by presenting them upside-down (i.e., rotated by 180°). To induce interocular suppression, we generated high-contrast, contour-rich CFS masks (9.2° × 9.2°) consisting of randomly arranged white, black, and gray circles (diameter 0.4°–1.8°; see Figure 1b).

An independent group of 16 observers answered two questions about 11 of the 12 regularly positioned object pairs (the two exemplars being counterbalanced across observers) in order to test if the two objects constituting a pair (a) were judged as commonly experienced together in this specific configuration and (b) were nevertheless perceived as two distinct objects. Participants answered on an ordinal scale from 1 ("fully disagree") to 7 ("fully agree"). For the first question ("I see these two objects often in this particular spatial arrangement") the mean of the average ratings for the different object pairs was high ($M = 5.78$), with little variability across pairs ($SD = 0.64$), demonstrating that the manipulation of regularity was successful. Also for the second question ("These are two distinct objects") ratings for the different object pairs were high with little variability ($M = 4.86$, $SD = 0.98$), meaning that despite the regularity manipulation the two individual objects constituting the pairs were still perceived as two separate objects.

Procedure

Each trial started with a 1-s fixation period. Subsequently, CFS masks changing at 10 Hz were presented to one eye, and a target stimulus was introduced to the other eye. To avoid abrupt gradients, target stimuli were gradually faded in over the first second of each trial (by linearly increasing the contrast and simultaneously decreasing the luminance from light- to midgray) and then remained constant until the end of the trial (Figure 1b). Beginning 2 s after trial onset, the contrast of the CFS masks was linearly decreased to zero over seven seconds. This contrast ramp was implemented to reduce the number of trials in which the target stimulus was not perceived at all. Target stimuli were presented until response or for a maximum trial duration of 10 seconds either to the left or to the right of the fixation dot (horizontal center-to-center distance 2.8°) at a random vertical position above or below the fixation dot (maximum vertical center-to-center distance 1.5°). Participants were required to press the left or the right arrow key on the keyboard to indicate whether the target stimulus appeared left or right to fixation. They were instructed to respond as soon as any part of the target stimulus became visible and to be as fast and accurate as possible. At the beginning of the experiment, participants were informed about the presentation of two vertically arranged objects on every trial, but no information regarding the regularity manipulation was provided.

There were 192 trials (separated by breaks after 64 and 128 trials) in which each combination of two pair configurations (regular, irregular), two target orientations (upright, inverted), 24 target exemplars, and two eyes for target stimulus presentation occurred once. Trial order was randomized, and the location of the target was selected at random for each trial.

Analysis

Only trials with correct responses and response times longer than 300 ms ($M = 98.0\%$, $SD = 1.4\%$) were

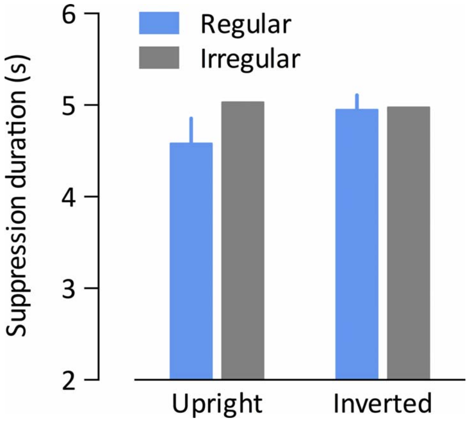

Figure 2. Results from Experiment 1. Bar plots show mean suppression durations for regular and irregular pairs, separately for target stimuli presented in their normal upright orientation, and in inverted orientation (i.e., rotated by 180°). Error bars denote 95% CIs for the mean difference between regular and irregular pairs, separately for upright and inverted targets.

included in the analyses. For our main analysis and for intuitive eyeballing of the results, we calculated means from the raw suppression durations. In addition, we conducted the same statistical analyses on log-transformed suppression durations to account for their positive skew (Heyman & Moors, 2014; Stein, End, & Sterzer, 2014; Stein, Thoma, & Sterzer, 2015). Throughout this paper, we report Cohen's *d* as an effect size estimate for the paired *t* tests, computed as the mean of the difference scores divided by the standard deviation of the difference scores.

Results

A repeated-measures ANOVA with the factors pair configuration (regular, irregular) and target orientation (upright, inverted) on the means calculated from the raw suppression durations revealed a significant main effect of pair configuration, $F(1, 13) = 9.62$, $p = 0.008$, $\eta_p^2 = 0.43$; a marginally significant main effect of target orientation, $F(1, 13) = 4.00$, $p = 0.067$, $\eta_p^2 = 0.24$; and, most importantly, a significant interaction, $F(1, 13) = 8.97$, $p = 0.010$, $\eta_p^2 = 0.41$. When targets were presented in their normal upright orientation, suppression durations for regular pairs were significantly shorter than for irregular pairs, $t(13) = -3.54$, $p = 0.004$, $d = 0.95$ ($M = -448$ ms, $SD = 473$ ms, 95% CI [−720 ms, −175 ms]; see Figure 2). Thus, regular object pairs overcame CFS and broke into awareness more quickly than irregular object pairs. Crucially, for inverted targets there was no significant difference in suppression durations between regular and irregular pairs, $t(13) = -0.39$, $p = 0.706$, $d = 0.10$ ($M = -29$ ms, $SD = 280$ ms, 95% CI [−191 ms, 133 ms]). Thus, differences in the grouping of simple image elements (which are preserved in inverted targets) are unlikely to account for the difference in suppression durations between upright regular and irregular pairs.

An additional analysis on the log-transformed suppression durations revealed a similar pattern of results: There was a significant main effect of pair configuration, $F(1, 13) = 9.73$, $p = 0.008$, $\eta_p^2 = 0.43$, and a significant interaction between pair configuration and target orientation, $F(1, 13) = 9.84$, $p = 0.008$, $\eta_p^2 = 0.43$, whereas the main effect of target orientation did not reach significance, $F(1, 13) = 2.32$, $p = 0.152$, $\eta_p^2 = 0.15$. For upright object pairs log-transformed suppression durations were significantly shorter for regular pairs than for irregular pairs, $t(13) = -3.80$, $p = 0.002$, $d = 1.01$, whereas no such difference was found for inverted pairs, $t(13) = -0.43$, $p = 0.677$, $d = 0.11$. These results show that object pairs that are positioned according to real-world regularities have an advantage in gaining access to awareness.

Linear mixed-effects analysis

To account for variability in suppression durations between individual stimulus items, we also performed linear mixed-effects analyses using the lme4 package (Bates, Maechler, & Bolker, 2012) for R (R Core Team) on the raw suppression durations and on the log-transformed suppression durations (for similar b-CFS analyses see Heyman & Moors, 2014; Stein, End, & Sterzer, 2014). These analyses had random intercepts for participants and for individual exemplars of the object pairs. Reduced models containing only these random effects of participants and pair exemplars were tested against models including fixed effects of pair configuration (regular, irregular) or target orientation (upright, inverted) using likelihood ratio tests. To test for the interaction effect, models with the pair configuration-by-target orientation interaction were compared to models with the two fixed factors only.

For the analysis of raw suppression durations, the comparison of the reduced model with the model containing the additional fixed factor of pair configuration was significant, $\chi^2(1) = 7.52$, $p = 0.006$, whereas the comparison with the model containing the additional fixed factor of target orientation was only marginally significant, $\chi^2(1) = 3.34$, $p = 0.068$. Most importantly, the interaction was significant, $\chi^2(1) = 5.65$, $p = 0.017$. Follow-up analyses for upright and inverted object pairs separately revealed that the main effect of pair configuration was significant only for upright pairs, $\chi^2(1) = 13.36$, $p < 0.001$, but not for inverted object pairs, $\chi^2(1) = 0.06$, $p = 0.810$. The results of the analysis of log-transformed suppression durations were similar, for pair configuration, $\chi^2(1) = 8.96$, $p = 0.003$, for target orientation, $\chi^2(1) = 2.18$, $p = 0.139$, and for the interaction, $\chi^2(1) = 6.31$, $p = 0.012$. Also for log-transformed suppression durations the main effect of pair configuration was significant only for upright pairs, $\chi^2(1) = 15.26$, $p < 0.001$, but not for inverted object pairs, $\chi^2(1) = 0.10$, $p = 0.751$. Thus, these results show that the influence of real-world regularities on access to awareness under CFS persisted after accounting for variability across individual object pair exemplars.

Experiment 2

A confirmatory second experiment was conducted to provide an internal replication (Experiment 2a) and to test the possibility that differences in the vertical position of individual objects could have accounted for the advantage of regular over irregular pairs in breaking CFS (Experiment 2b). Although regular and irregular pairs consisted of identical single objects that only differed in their configuration, these individual objects occupied slightly different spatial locations depending on whether they belonged to a regular or irregular pair: Objects that were presented on top of other objects in regular pairs (e.g., bathroom mirror) appeared on average further up in the CFS frames when they were part of a regular pair than when they were part of an irregular pair. Conversely, objects that were presented below other objects in regular pairs (e.g., bathroom sink) appeared on average further down in the CFS frames when they were part of a regular pair than when they were part of an irregular pair. In Experiment 2b, we presented single objects at the same positions as in the regular and irregular pairs. If the positioning of individual objects was driving the effect, we would expect to obtain shorter suppression durations for single objects that appeared at the same positions as in the regular pairs. If, however, faster awareness of regular pairs was related specifically to the relative positioning of the two objects forming a pair, i.e., to their real-world configuration, no effect would be expected for single objects.

Method

Participants

Experiment 2a was an identical replication of Experiment 1. For this confirmatory study we decided to run a larger sample size than in Experiment 1, in order to have sufficient power for detecting the effect of interest. We therefore decided to add another 10 participants to the sample size of Experiment 1, resulting in a total N of 24. Based on the effect size estimation from Experiment 1, this sample size yielded a power of 0.96 for obtaining the critical interaction between pair configuration and object orientation. This new set of 24 volunteers (21 female, age range 18–33 years, mean 22.7 years) participated for course credits or payment.

Apparatus, stimuli, and procedure

Experiment 2a was identical to Experiment 1. Experiment 2b was designed to control for differences between regular and irregular pairs regarding the vertical position of individual objects on the screen. For Experiment 2b, we created single-object stimuli by replacing either the top or the bottom object from the regular and irregular pair images with the light-gray background. This resulted in a set of 48 "regular" and 48 "irregular" single-object target stimuli (24 "top objects," e.g., bathroom mirror, and 24 "bottom objects," e.g., bathroom sink, respectively, in each of their two possible positions within a pair). Only upright versions of these single objects were included in Experiment 2b.

The general procedure was identical to Experiment 1. The positions at which "regular" and "irregular" single-object targets could appear were the exact same positions at which the individual objects in regular and irregular pairs could appear. Experiment 2b contained 192 trials (separated by breaks after 64 and 128 trials) in which each combination of two target conditions ("regular," "irregular"), 48 target exemplars (24 "top objects," 24 "bottom objects"), and two eyes for target stimulus presentation occurred once. Trial order was randomized, and the location of the target was selected at random for each trial. Half of the participants began with Experiment 2a, and the other half with Experiment 2b. The two experiments were separated by a short break.

Analysis

Again, only trials with correct responses and response times longer than 300 ms (Experiment 2a: $M = 97.8\%$, $SD = 1.8\%$; Experiment 2b: $M = 97.8\%$, $SD = 1.7\%$) were included in the computation of raw suppression durations and in the additional analysis of log-transformed suppression durations.

Results

Experiment 2a – Replication

The results of Experiment 2a replicated the findings of Experiment 1: A repeated-measures ANOVA with the factors pair configuration (regular, irregular) and object orientation (upright, inverted) revealed a marginally significant main effect of pair configuration, $F(1, 23) = 4.00$, $p = 0.058$, $\eta_p{}^2 = 0.15$, no significant main effect of object orientation, $F(1, 23) = 1.99$, $p = 0.172$, $\eta_p{}^2 = 0.08$, but a significant interaction, $F(1, 23) = 14.30$, $p = 0.001$, $\eta_p{}^2 = 0.38$. For upright object pairs,

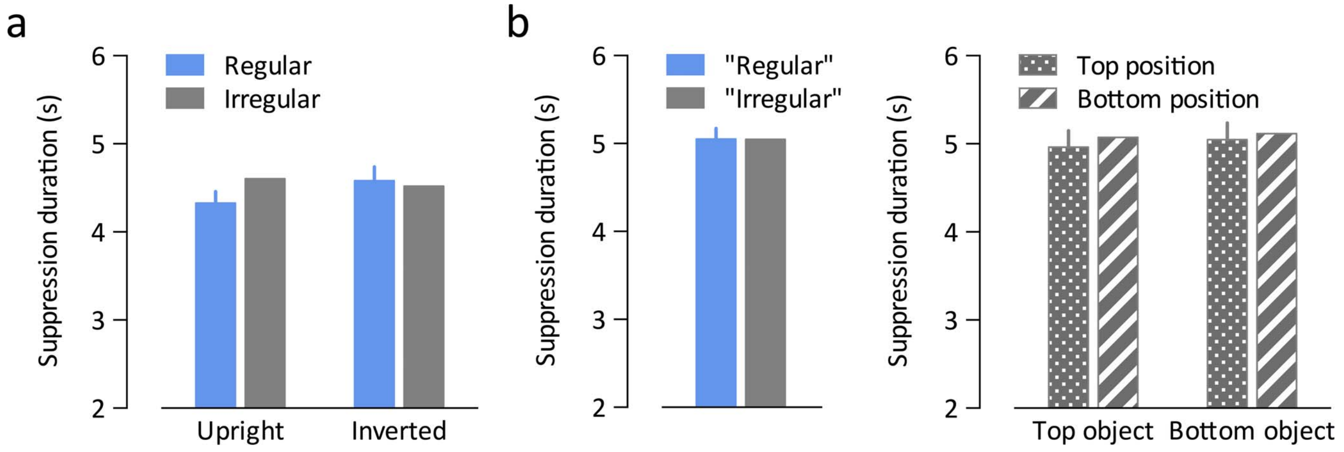

Figure 3. Results from Experiment 2. (a) Results from Experiment 2a, which was an exact replication of Experiment 1. Bar plots show mean suppression durations for regular and irregular pairs, separately for target stimuli presented in their normal upright orientation and in inverted orientation. Error bars denote 95% CIs for the mean difference between regular and irregular pairs, separately for upright and inverted targets. (b) Results from Experiment 2b, which served to control for differences in the vertical position of individual objects in the previous experiments. The bar plots on the left denote mean suppression durations for individual objects derived from regular pairs and irregular pairs. The bar plots on the right show mean suppression durations for single objects as a function of target position (top: above fixation, bottom: below fixation) and object type, i.e., depending on whether the single object was presented on top of another object in the original pairs (top object, e.g., bathroom mirror) or below another object in the original pairs (bottom object, e.g., bathroom sink). Error bars denote 95% CIs for the mean difference between single objects from regular and irregular pairs and between top and bottom positions, respectively.

suppression durations were again significantly shorter for regular pairs than for irregular pairs, $t(23) = -4.43$, $p < 0.001$, $d = 0.90$ ($M = -276$ ms, $SD = 306$ ms, 95% CI [−405 ms, −147 ms]; see Figure 3a). As in Experiment 1, there was no significant difference in suppression durations between regular and irregular pairs when they were shown in inverted orientation, $t(23) = 0.81$, $p = 0.428$, $d = 0.16$ ($M = 62$ ms, $SD = 375$ ms, 95% CI [−97 ms, 220 ms]).

Again, an additional analysis of the log-transformed suppression durations confirmed these findings: There was a significant main effect of pair configuration, $F(1, 23) = 4.33$, $p = 0.049$, $\eta_p{}^2 = 0.16$, no significant main effect of object orientation, $F(1, 23) = 1.93$, $p = 0.178$, $\eta_p{}^2 = 0.08$, but a significant interaction, $F(1, 23) = 11.30$, $p = 0.003$, $\eta_p{}^2 = 0.33$. Log-transformed suppression durations for regular pairs were significantly shorter than for irregular pairs when presented in upright orientation, $t(23) = -4.39$, $p < 0.001$, $d = 0.90$, but not when presented in inverted orientation, $t(23) = 0.77$, $p = 0.452$, $d = 0.16$. These results confirm the findings of Experiment 1, again demonstrating that objects positioned according to real-world regularities gain privileged access to awareness.

Linear mixed-effects analysis

In addition, as for Experiment 1 we carried out a linear mixed-effects analysis to account for variability between individual object pair exemplars. The analysis of raw suppression durations yielded no significant main effects of pair configuration, $\chi^2(1) = 2.70$, $p = 0.010$, or target orientation, $\chi^2(1) = 1.81$, $p = 0.179$, but, importantly, a significant interaction, $\chi^2(1) = 7.11$, $p = 0.008$. The main effect of pair configuration was significant only for upright pairs, $\chi^2(1) = 9.40$, $p = 0.002$, but not for inverted object pairs, $\chi^2(1) = 0.49$, $p = 0.486$. Similarly, the analysis of log-transformed suppression durations yielded no significant main effects of pair configuration, $\chi^2(1) = 2.52$, $p = 0.112$, or target orientation, $\chi^2(1) = 1.69$, $p = 0.193$, but a significant interaction, $\chi^2(1) = 6.55$, $p = 0.011$. Again, the main effect of pair configuration was significant only for upright pairs, $\chi^2(1) = 8.67$, $p = 0.003$, but not for inverted object pairs, $\chi^2(1) = 0.43$, $p = 0.513$. Thus, these results show that also in Experiment 2a the beneficial influence of real-world regularities on access to awareness persisted after accounting for variability across individual object pair exemplars.

Experiment 2b – Single-objects control

To test whether this effect could have been due to the slightly different positioning of individual objects in regular and irregular pairs, we compared suppression durations for single objects that appeared at the same spatial locations as in the pairs. Crucially, there was no significant difference in suppression durations between single objects from regular and irregular pairs, $t(23) = 0.07$, $p = 0.941$, $d = 0.02$ ($M = 4$ ms, $SD = 268$, 95% CI

[−109, 117]; see Figure 3b). Moreover, when directly comparing Experiment 2a and 2b, the difference in suppression durations between (upright) regular and irregular pairs was larger than between "regular" and "irregular" single objects, as reflected in a significant interaction between experiment and configuration, $F(1, 23) = 7.67$, $p = 0.011$, $\eta_p^2 = 0.25$.

The analysis of log-transformed suppression durations from Experiment 2b revealed similar results: There was no significant difference between single objects from regular and irregular pairs, $t(23) = -0.57$, $p = 0.576$, $d = 0.12$, and the advantage of (upright) regular over irregular pairs in Experiment 2a was larger than the difference between "regular" and "irregular" single objects, $F(1, 23) = 6.70$, $p = 0.016$, $\eta_p^2 = 0.23$. Thus, the relative position of individual objects cannot explain the advantage of regular over irregular pairs in access to awareness.

Finally, we further explored whether spatial locations influence access to awareness of objects as a function of whether an object is typically seen on top or below other objects. Objects that are typically seen above other objects generally more often fall in the upper part of the visual field and could thus be detected better when appearing in the upper as compared to the lower visual field, whereas objects that are typically seen below other objects more often fall in the lower visual field and might be detected better there. To address this possibility, we computed mean suppression durations depending on the position of the target (above vs. below fixation) and the type of object ("top object," e.g., bathroom mirror, vs. "bottom object," e.g., bathroom sink). An ANOVA yielded no significant main effects of target position, $F(1, 23) = 2.64$, $p = 0.118$, $\eta_p^2 = 0.10$, or object type, $F(1, 23) = 1.57$, $p = 0.223$, $\eta_p^2 = 0.06$, and, most importantly, no significant interaction, $F(1, 23) = 0.10$, $p = 0.759$, $\eta_p^2 < 0.01$, meaning that the spatial location in the CFS frames did not influence breakthrough into awareness differently for different types of objects (see Figure 3b). Similarly, the analysis of log-transformed suppression durations yielded no significant main effects of target position, $F(1, 23) = 1.37$, $p = 0.254$, $\eta_p^2 = 0.06$, or object type, $F(1, 23) = 2.32$, $p = 0.141$, $\eta_p^2 = 0.09$, and no significant interaction, $F(1, 23) = 0.09$, $p = 0.765$, $\eta_p^2 < 0.01$. These results further support the notion that the difference in suppression duration between regular and irregular pairs is due to the configuration of the pairs rather than to their positions on the screen.

Discussion

The present results demonstrate that objects that can be grouped based on real-world spatial regularities are prioritized for access to conscious awareness. Two experiments revealed faster access to awareness for object pairs that were positioned in the configuration in which they typically co-occur in the real world. This advantage of regularly positioned object pairs was abolished by stimulus inversion, meaning that the effect cannot reflect physical stimulus differences or grouping of simple image elements. Rather, our findings indicate that experience-based grouping of complex, meaningful objects can occur before these objects become available for conscious access, thereby determining which objects are consciously perceived in the first place.

This advantage for grouped objects is similar to the advantage in breaking CFS for simple shapes that can be grouped to a Kanizsa figure through illusory contours (Wang et al., 2012). Thus, both grouping of simple stimuli (also see Montoro, Luna, & Ortells, 2014) as well as grouping of meaningful, complex stimuli can transpire before conscious access. The underlying mechanisms, however, are most likely markedly different. The representation of physical (e.g., geometrical) relationships among simple stimuli, such as those leading to the formation of illusory contours, seems to rely on both early visual cortical areas and higher-level ventral stream areas (e.g., Abu Bakar, Liu, Conci, Elliott, & Ioannides, 2008; Stanley & Rubin, 2003; von der Heydt, Peterhans, & Baumgartner, 1984), whereas the representation of object-object relations likely involves only higher occipitotemporal object processing areas (Kim & Biederman, 2010; Roberts & Humphreys, 2010). Distributed patterns of activity in these areas evoked by two objects can be modeled as a linear combination of the response patterns to the individual objects (MacEvoy & Epstein, 2009; Reddy, Kanwisher, & VanRullen, 2009) and the relative weighting of the two patterns seems to be altered when the two objects form meaningful spatial relationships (Baeck, Wagemans, & Op de Beeck, 2013; but see also Kaiser, Strnad, Seidl, Kastner, & Peelen, 2014), indicating that these object configurations are represented in visual cortex activity patterns. Furthermore, Kanizsa-type figures do not only induce the perception of illusory contours but also of an illusory surface, which constitutes a salient region that "pops out" in visual search (Davis & Driver, 1994; Gurnsey, Poirier, & Gascon, 1996). Thus, differences in suppression durations for these stimuli may reflect differences in preconsciously extracted bottom-up saliency (cf. Gayet et al., 2014). By contrast, the present findings cannot be due to differences in bottom-up saliency, but must reflect knowledge about the relative positions of objects that often co-occur in the real world.

This central role of real-world perceptual experience in modulating access to visual awareness is consistent with findings from other studies showing that the dynamics of interocular competition are influenced by experience with our environment (Gayet et al., 2014). For example, stimuli whose low-level properties follow natural image statistics tend to dominate perception in binocular rivalry (Baker & Graf, 2009). Also natural objects such as human faces and bodies overcome CFS more quickly when they are presented in their familiar upright orientation than when their typical spatial configuration is disrupted by inversion (e.g., Jiang et al., 2007; Stein, End, & Sterzer, 2014; Stein, Peelen, & Sterzer, 2011; Stein, Sterzer, & Peelen, 2012; Yang, Zald, & Blake, 2007; Zhou, Zhang, Liu, Yang, & Qu, 2010). The present results go beyond these previous studies by showing for the first time that the relative spatial position of two upright, locally identical objects can determine access to awareness. Thus, while previous findings can be explained by a general advantage for more recognizable or meaningful stimuli (e.g., upright faces), differences in recognizability of individual objects cannot explain our results, because individual stimuli were identical across conditions. Only the relative positioning can render regular object pairs more meaningful and facilitate their recognition (Gronau & Schachar, 2014; Roberts & Humphreys, 2011; Tobon et al., 2014). The present findings may thus reflect the increased meaningfulness of coherent object pairs, indicating that inter-object grouping can precede conscious access.

How, then, could object grouping influence the duration of perceptual suppression? According to the unconscious binding hypothesis, spatiotemporally distributed visual stimuli can be bound into coherent objects even when rendered invisible (Lin & He, 2009). Indeed, the advantage of radial over random motion in b-CFS (Kaunitz, Fracasso, Lingnau, & Melcher, 2013) indicates that the visual system can extract physical regularities from suppressed stimuli to form coherent patterns, which are then prioritized for conscious access. Interobject grouping that emerges from such preconscious binding of individual objects may similarly entail the formation of coherent, integrated multiobject representations, either through neural assemblies in object-sensitive cortex or through context-facilitated reentrant circuitry between frontal and occipitotemporal areas (Fenske, Aminoff, Gronau, & Bar, 2006). This unified representation of regularly positioned objects seems to be a more potent competitor for access to the capacity-limited stage of conscious awareness than the representations of single objects alone. This conclusion is consistent with the general notion that b-CFS is sensitive to complex stimulus properties such as familiarity, ecological relevance, or meaningfulness, whereas the extraction of even more complex stimulus attributes, such as word semantics, may require conscious access (Gayet et al., 2014).

Several previous studies have used this approach to study unconscious processing transpiring specifically under interocular suppression (e.g., Jiang et al., 2007; Mudrik, Breska, Lamy, & Deouell, 2011; Stein, Senju, Peelen, & Sterzer, 2011; Wang et al., 2012; Zhou et al., 2010). These studies included a binocular control condition not involving interocular suppression and inferred CFS-specific unconscious processing when the effect obtained with b-CFS was larger than the effect obtained with this control condition. However, because the logic of relying on such a control condition for inferring CFS-specific unconscious processing has recently been questioned on theoretical and empirical grounds (Stein, Hebart, & Sterzer, 2011; Stein & Sterzer, 2014), here we did not include such a binocular control condition (also see e.g., Gray, Adams, Hedger, Newton, & Garner, 2013; Stein, End, & Sterzer, 2014; Stein et al., 2015; Stein, Seymour, Hebart, & Sterzer, 2014; Tsuchiya, Moradi, Felsen, Yamazaki, & Adolphs, 2009; Yang et al., 2007). The current findings could thus reflect more general differences in detectability between regularly and irregularly positioned object pairs rather than differences in CFS-specific unconscious processing. Still, such differences in stimulus detectability can be argued to reflect differences in the processes that precede and lead to conscious access (e.g., Kaunitz et al., 2013).

To provide unequivocal evidence for unconscious processing differences between regular and irregular object pairs, future studies will need to show that real-world spatial regularities continue to be extracted from objects that are rendered permanently invisible. However, this approach may be less sensitive to the visual processes that precede conscious access than the b-CFS paradigm in which initially invisible stimuli eventually cross the threshold to consciousness. For example, neuroimaging studies have repeatedly shown that the processing of stimuli rendered permanently invisible through CFS is strongly reduced in those higher-level visual areas along the ventral stream that are likely candidates for representing spatial regularities among complex objects (for a review, see Sterzer, Stein, Ludwig, Rothkirch, & Hesselmann, 2014). Because to date no study has investigated the spatiotemporal dynamics of the neural processes associated with competition for awareness during b-CFS, it remains possible that the advantage of regular over irregular pairs in b-CFS involves occipitotemporal and even frontal cortices.

Another important challenge for future work will be to investigate to what extent these findings obtained with the laboratory paradigm of b-CFS extend to other paradigms for measuring access to awareness and, most importantly, to more naturalistic situations and to real-world perception. Although b-CFS seems to be a particularly sensitive device for probing differences in stimulus detectability, recent studies that used both b-CFS and other psychophysical paradigms for studying access to awareness have shown similar effects with b-CFS and standard sandwich masking (Stein, Seymour, et al., 2014) and rapid serial visual presentation (Gobbini et al., 2013). It is thus likely that findings obtained with b-CFS can similarly be found with other, sufficiently sensitive psychophysical laboratory techniques. One promising avenue for determining the extent to which perceptual mechanisms uncovered with such laboratory experiments influence behavior in real-world situations consists in using more naturalistic stimulus material, such as photographs of real-world scenes (for a review, see Peelen & Kastner, 2014). For example, the current stimuli could be embedded in naturalistic scenes to test whether interobject grouping facilitates perceptual performance in a more ecological setting.

Whereas our results show that objects in regular configurations are prioritized for conscious access, another recent b-CFS study found shorter suppression durations for photographs of complex scenes that contained semantically incongruent objects, for example a checkerboard in an oven (Mudrik et al., 2011). However, in contrast to the present approach in which we only changed the configuration of identical objects, this study compared suppression durations to physically different stimuli and could therefore not rule out that these results reflected visual rather than semantic factors. Nevertheless, their findings suggest that gross violations of semantic context are rapidly detected, bringing an unexpected stimulus more quickly into awareness, perhaps through a preconscious novelty or surprise response. This advantage of incongruent scenes is not necessarily inconsistent with the present findings, as the two objects in our irregular condition were always semantically congruent. Thus, in the absence of gross semantic violations, the visual system is tuned to those stimuli that are typically encountered in real-world environments. The present findings now demonstrate that this principle applies even to the complex spatial-relational regularities among natural objects: Objects that follow these real-world regularities are prioritized for conscious access.

Keywords: grouping, object perception, real-world regularities, visual awareness, continuous flash suppression

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Corresponding author: Timo Stein.
Email: timo@timostein.de.
Address: Center for Mind/Brain Sciences, University of Trento, Rovereto, Italy.

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