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Depth from blur and grouping under inattention

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Abstract

Previous studies provided evidence in support of attention operating in three-dimensional space, and the iterative and multi-stage nature of organizational processes in relation to attention and depth. We investigated depth perception and attentional demands in grouping organizations that contain blur as a depth cue. Contrary to previous studies, in our displays, no depth from occlusion could be implied from a shared border between groups or surfaces. To evaluate depth perception, subjective reports were collected where participants indicated which elements, blurry or sharp, they perceived as closer. To examine whether depth perception from blur can alleviate attentional demands, we used an inattention paradigm. We presented displays of grouping organizations by collinearity or color similarity that were previously found to require attention and added blur to the figure or the background elements to generate depth perception. In addition, we presented similar displays containing grouping by blur similarity as a single cue. We hypothesized that adding blur would facilitate the segmentation of element groups due to their perceived depth, which might lead to a diminished demand for attention. Our results confirmed that blur led to depth perception, and that sharp elements were perceived as closer more frequently than blurry elements. Thus, these results provide novel evidence for depth from blur in grouping where no inference of occlusion can be derived from a border. However, although the results suggest that blur information was processed under inattention, little evidence was found for decreased attentional demands for grouping processes in the presence of blur.

Keywords Attention · Divided Attention and Inattention · Grouping andSegmentation · 3D perception · Depth and shape from X

Introduction

Our visual environment is usually cluttered, containing many fragments of information that need to be put together in order to provide a coherent percept of the world. To construct clear images from this clutter, the visual system uses principles of grouping and figure–ground segmentation. These operations were once thought to belong to a unified process of perceptual organization. However, recent studies have revealed a more complex picture, as grouping principles were found to differ in their time courses, developmental trajectories, attentional demands, and neural correlates (for comprehensive reviews on Gestalt factors in visual perception see Peterson & Kimchi, 2013; Wagemans et al., 2012). The role attention plays in perceptual organization has been debated for decades. While earlier theories postulated that grouping and figure–ground segmentation were providing preliminary units for processing, implying they were early and preattentive operations (e.g., Julesz, 1981; Marr, 1982; Neisser, 1967; Treisman, 1982), more recent studies support the view that perceptual organization processes operate in iterations before and after constancies and depth perception are achieved (Palmer et al., 2003).

Perceptual organization and depth perception

The figure is usually defined as the object positioned in front of the ground, which in turn is perceived as continuing behind the figure. A study by Peterson and Gibson (1993) demonstrated that depth cues alter figure–ground perception, by presenting participants with stereograms in which a figural cue (i.e., familiarity) was compatible or incompatible with stereoscopic depth (i.e., the

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familiar figure could appear in the front plane of the stereogram or in the back plane, respectively). Peterson and Gibson (1993) found that in the incompatible condition figure–ground perception was practically ambiguous, as reversals of the organizations were frequent compared with the compatible condition. Grouping processes, however, show a more complex relationship with depth perception. As pointed out by Palmer et al. (2003), grouping can occur before and after depth perception is achieved. For example, elements grouped by proximity, common region, or connectedness were perceived to be grouped differently when viewed monocularly or stereoscopically. Notably, once stereoscopic depth had been achieved, the elements were grouped according to their common depth plane. This finding suggests that grouping follows depth perception. However, depth perception can also be affected by grouping. Palmer and Brooks (2008) demonstrated that grouping of elements and an edge of a surface by a shared feature (such as blurriness, common fate, proximity, or color) instigated figure–ground assignment, and the perception of the figural surface as being closer to the participant.

According to Palmer and Brooks (2008), grouping and figure–ground processes have a strong mutual influence. This is of particular interest when the role of attention in perceptual organization is considered because the role of attention in figure–ground segmentation is still not clear. On the one hand, it has been demonstrated that figural assignment can be achieved outside of focused attention (Kimchi & Peterson, 2008). On the other hand, it has also been shown that attention can influence figural assignment (Peterson & Gibson, 1994; Vecera et al., 2004). Baylis and Driver (1995) have theorized that the relationship between attention and figural assignment may include different mechanisms of attention, proposing (a) that bottom-up factors determine figural assignment, which in turn determines exogenously the distribution of attention, and (b) that a strategic and endogenous directing of attention can resolve ambiguous cases. When the layer of grouping is added, a complex process involving all these factors needs to take place. In some cases, attention will be needed for grouping to occur and then allow figural assignment. In others, grouping will determine figure–ground segmentation and attention will be drawn to the figure. It is also possible that figural assignment will be determined according to relative depth, in which a closer surface is usually perceived as the figure, and then attention drawn to the figure may aid the grouping of the surface elements and border. We do not aim for the current study to provide a simple answer to this intriguing question about the relationship between grouping, attention, and depth perception. Instead, we chose to examine certain aspects of this complex relationship—namely, the effect that depth perception may have on grouping processes where grouping is presumed to result in figural assignment, and whether this requires attentional resources.

Grouping under inattention

A recent line of studies focused on how attentional requirements change as a function of the operations that are involved in the organization (Kimchi & Peterson, 2008; Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017a). Kimchi and Razpurker-Apfeld (2004) proposed that there is a continuum of attentional demands in perceptual organization when their results showed that some organizations based on color similarity such as grouping into rows and columns could be achieved without focused attention, while other organizations such as grouping dots into an individual line embedded in a background could not. Later, Rashal et al. (2017a) demonstrated that the need for attention in grouping organizations varied depending on the grouping principle constructing the organization. This is because rows and columns organizations were achieved without focused attention when constructed by proximity but not when constructed by shape similarity. In addition, they proposed that attentional demands depend on the complexity of the process that needs to take place for a grouping organization to be achieved. This is because organizations that required contingent processes of element segregation and shape formation, such as grouping elements into a shape due to their collinearity, were not achieved without attention when the collinear elements were embedded in a background of randomly oriented elements but did not require attention when no background elements were present.

Thus, these studies suggest that visual processing is effortful in most situations since real-world visual scenes are rarely constructed by one simple organizational principle. One caveat of this line of research is that the organizations that were tested were always two-dimensional; however, real-world visual scenes include depth information. In the current study, we investigated whether organizational processing can be less effortful when this information is provided. In this context, we examined whether depth information from blur can alleviate attentional demands in simple and complex grouping organizations based on collinearity and color similarity.

Attention in depth

Research on the relationship between attention and depth perception provides evidence for the effect depth cues have on the allocation of attentional resources (e.g., Atchley et al., 1997; Downing & Pinker, 1985; Enns & Rensink, 1990; Humphreys & Donnelly, 2000; Kleffner & Ramachandran, 1992; Marrara & Moore, 2000). For example, Atchley et al. (1997) demonstrated larger object-based effects (i.e., a larger cost for identifying a target on an unattended object compared with identifying an equally distant target located on an attended object in a noncued location), for objects that were located on the same depth plane compared with when the objects were on different depth planes. Marrara and Moore (2000) explored the conditions in which attention is allocated to different depth planes. Using a cueing paradigm, they showed facilitation of target identification when the surface in depth where the target was about to appear was validly cued, compared with invalidly cued targets. This finding was not restricted to the target being located within one contiguous object but was also found when placeholders were distributed across the display. Importantly, when the same placeholders were distributed across depth planes no such facilitation was found. Interestingly, though, when placeholders that were similar in color were distributed across different depth planes, facilitation for validly cued targets was also found, indicating that attention can be allocated in depth following grouping processes. Other studies showed that visual search utilizes a three-dimensional representation of objects in an array presented on a single plane (e.g., Enns & Rensink, 1990; Humphreys & Donnelly, 2000; Kleffner & Ramachandran, 1992), supporting the view that attention operates in three-dimensional space.

Blur as a cue for grouping and depth

In the current study, we chose to focus on blur as a depth cue. Blur has been shown to affect depth perception, as it has been found to be correlated with the amount of surface blur (e.g., Marshall et al., 1996; Mather & Smith, 2002; O'Shea et al., 1997). Notably, blur does not provide the sign for the distance of the object from the participant (i.e., whether it is closer or farther away), as it occurs in normal vision when the object is near or far from the plane of focus. It has been suggested that resolving the sign problem with blurry surfaces occurs through *occlusion edge blur*, as the blurriness of the border between two textures is affiliated with the texture with a similar amount of blur, leading to the perception of occlusion where that texture is perceived to be in front of the other one (Marshall et al., 1996; Mather, 1996). Later, Palmer and Brooks (2008) reported a related grouping effect (edge-region grouping [ERG]), extending it to surfaces comprised of discrete elements and a line that functioned as a border due to similarity by blur. In that study, participants indicated which of two areas they perceived as closer/figural, while the blurriness of the border between them and the elements on both sides were manipulated independently. Their results showed that depth perception was achieved in these displays. However, the perception of one area as figural and closer was more frequent when the border and surface elements were sharp compared with blurry. Thus, figural status may have been affected by an inherent bias towards perceiving blur as an attribute of the background.

Our aim in this study was thus twofold, as we investigated both depth perception and attentional demands in grouping organizations that contain blur to provide depth. To that end, we adapted grouping organizations that have been shown to require attention in previous studies, such as a shape formed by color similarity or by collinearity (see Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017a, respectively, for the original displays), by applying blur to the elements constructing them (Experiments 1a–b and 2a–b). Blur was added either to the figural or the background group in the organization. In addition, new stimuli were created with similar figure–ground organizations to the ones used in Experiments 1–2, but now only blur similarity was used as a single grouping cue (Experiments 3a–b). To evaluate depth perception in our displays, subjective reports were collected where participants reported whether they perceived the blurry or nonblurry elements in the display as closer to them. In particular, we were interested to see whether depth would follow figural assignment. Normally, the object of focus (i.e., on the horopter) is perceived as sharp, while objects behind or in front of it are blurred. Thus, it is possible that the groups of elements forming the figure would be perceived as closer than the other group irrespective of their blurriness, due to the focus placed on them. However, groups of sharp elements may be perceived as closer more frequently, as has been found previously (Palmer & Brooks, 2008), with minimal consideration to the role of the group of elements in the display. Still, in contrast to the studies mentioned above, the groups of elements in our displays were not defined by a border. Thus, if an occlusion border is necessary to resolve the sign problem, depth perception in our displays will remain ambiguous.

To examine whether depth perception due to blur can alleviate attentional demands in grouping we used the inattention paradigm with an online measure (Driver et al., 2001; Kimchi & Peterson, 2008; Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017a; Russell & Driver, 2005). This paradigm, which is described in detail in the Methods section, was designed to reveal congruency effects between a change in the task-relevant stimulus and a change in its unattended backdrop. The hypothesis is that congruency effects will emerge (i.e., better performance in trials where a change in the target is congruent, rather than incongruent, with a change in the backdrop), as long as the backdrop contains organizations that can be accomplished without focused attention. Thus, if the addition of blur to other grouping organizations can reduce the demand for attention in the organizations that previously were found to demand attention, congruency effects may emerge. If, however, depth from blur cannot facilitate processing of grouping under inattention, congruency effects should not emerge here, replicating previous results.

Both the subjective reports and the inattention parts of the experiments were conducted with the same participants in one session, except for Experiment 1a, where different participants performed the different tasks. Subjective reports of depth perception were collected after the inattention part of the experiments, so that the participants would not be made aware of the organizations in the backdrop displays, which would hamper inattention conditions. However, the Methods and Results sections describe the two parts in reversed order to match the logic of the study.

Experiments 1a and 1b

Methods

Participants

A total of 31 students from KU Leuven participated in Experiment 1a (12 in the subjective reports part and another 19 in the inattention part), and 22 others participated in Experiment 1b. Since many experiments using the inattention paradigm resulted in null effects, the minimal sample size in this study was based on the number of participants in an experiment showing a significant effect of $\eta_p^2 = 0.36$ (Rashal et al., 2017a). All had normal or corrected-to-normal vision and normal color vision. None participated in more than one experiment, and all were naïve to the purpose of the study. The study was approved by the KU Leuven Ethics Committee, and all the participants provided written informed consent in accordance with the Declaration of Helsinki.

Apparatus

The stimuli were presented using PsychoPy software (Peirce, 2007) on a 24-in. LCD Dell Monitor U2410, controlled by a Dell PC optiplex 780 computer. The experiment was conducted in a dimly lit room. The participants rested their heads on a chin rest at a viewing distance of 57 cm and watched the screen through a circular aperture of a matte black cardboard sheet.

Subjective reports of depth perception: Stimuli

Experiment 1a: Shape by Collinearity Illustration of the displays are presented in Fig. 1.[1] The displays were created using GIMP (The GIMP Development Team, 2019). The elements were solid ellipses (1° × 0.5° each) in various orientations. Each display consisted of 60 elements of one color (red or green: RGB 102, 25, 10, or 10, 102, 94, respectively), scattered around the target matrix on a 9.5° × 9.5° area. To obtain blur we used a Gaussian blur filter with a radius of three pixels. A subset of the elements in each display was grouped by collinearity to form a cross or a square (12 or 16 elements, respectively). The other elements of each display were randomly oriented. On half of the trials the elements composing the shape were blurred, while the background elements were sharp, and on the other half the background elements were blurred and the elements composing the shape were sharp. To control for the possibility of detecting a change in the backdrop grouping from local changes of just a few elements the color and orientation of the elements always changed between successive displays (red in the first and green in the second, or vice versa), and some elements changed their location, regardless of whether the organization changed or not.

Experiment 1b: Shape by color similarity Forty-nine circle elements, each 0.48° in diameter, were spread at equal distances in a 7 × 7 matrix within a 9.1° × 9.1° area. Each display contained elements in two colors (blue and yellow/red and green: RGB 47, 37, 125 and 244, 224, 40; or 214, 9, 17, and 0, 145, 104, respectively), and both changed between successive displays (blue and yellow in the first, and red and green in the second, or vice versa). The distance of the most central elements from the target matrix was 0.9°.

Design and procedure

Each display was presented for 200 ms, the same duration as in the inattention experiment. In Experiment 1a, the participants reported for each display whether they perceived the shape in the display to be closer or farther relative to the other group of elements. In Experiments 1b (as well as in the following experiments), participants were prompted with the question, "Which of the ellipses/dots you perceived to be closer?," and they could choose between "blurry," "non-blurry," and "they were on the same plane." The experimenter made sure the participants could recognize the blurry and sharp (i.e., nonblurry) elements and instructed them to indicate their first impression. There was no time constraint for the response. Each of the eight displays was presented seven times in a random order, resulting in 56 trials in total in each experiment.

Inattention experiments: Stimuli

The displays described above were used in the inattention experiment that followed as backdrop displays. In addition, each display included a target at the center of the display

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[1] Examples of the original stimuli are included in the Supplementary Material. It is advised to view the original stimuli at the proper size and resolution as reported in the manuscript. Still, variation may occur due to different screens.

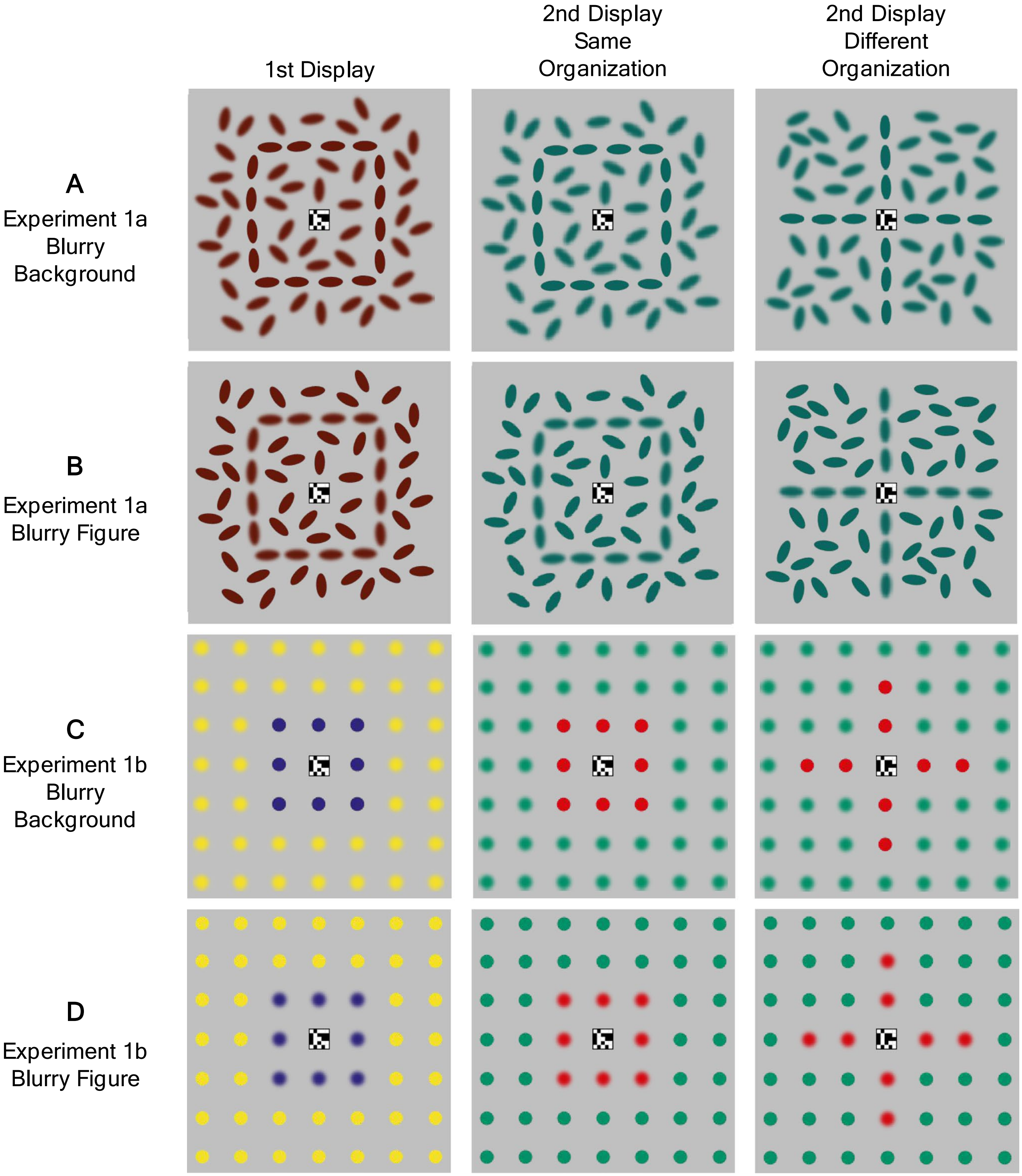

Fig. 1 Illustrations of the backdrop stimuli employed in Experiment 1a (collinearity grouping) and Experiment 1b (color similarity grouping). On half of the trials, the background was blurry (**a** and **c**), and on the other half the figure was blurry (**b** and **d**). See text for details. (Color figure online)

surrounded by the backdrop grouping organization. The target consisted of 12 black and 13 white small solid squares, 0.19° each, randomly located in a 5 × 5 matrix subtending 0.95° × 0.95°. The target matrix changed between two successive displays in half of the trials and stayed the same in the other half. The change was made by switching the location of one small white square with one small black square within the matrix.

Design

The design was a 2 (target: same, different) × 2 (backdrop organization: same, different) × 2 (blur: background, figure) within subject. All the combinations of backdrop organization and target were randomized within blocks, with each combination occurring on an equal number of trials. On half of the trials, the target changed between successive displays, and on the other half of the trials the target stayed the same. Independently of whether the target changed or remained the same on each trial, the organization in the backdrop (i.e., columns/rows) also changed or remained the same. Blur conditions (background or figure) were randomly presented across blocks independently from the manipulation of the other factors, with the constraint that both displays of a presented trial belonged to the same blur condition (e.g., blurry figure in both displays). There were 320 experimental trials administered in four blocks, preceded by 16 practice trials.

Procedure

The procedure was identical to the one described in Rashal et al. (2017a; see also Kimchi & Peterson, 2008; Kimchi & Razpurker-Apfeld, 2004). The sequence of events in a trial is depicted in Fig. 2. Each trial started with a fixation cross that appeared for 250 ms in the center of the screen. After an interstimulus interval (ISI) of 250 ms, the first display appeared for 200 ms followed by a 150 ms ISI, after which the second display appeared for 200 ms. Then, the participants had to indicate whether the two successive target matrices were the same or different, by pressing one of two designated keys on the keyboard. The participants were instructed to respond as rapidly and accurately as possible. Reaction time (RT) was measured from the appearance of the second display until a response was made. Feedback about an incorrect response was provided by an auditory tone as soon as the participant responded, or if no response was made within 3 seconds. The intertrial interval (ITI) was 1,000 ms. To confirm that the participants were not attending the backdrop, they were asked questions about the backdrop display immediately following the last trial. The first question was, "What was the shape in the backdrop?" The two alternatives were "square" or "cross." The second question was, "Was there a change in the shape in the backdrop organization across the two displays in the last trial?" The two alternatives were "change" and "no change."

Results and discussion

Statistical analyses were conducted using R (R Core Team, 2016), with ez (Lawrence, 2015), BayesFactor (Morey & Rouder, 2015), and effectsize (Ben-Shachar et al., 2020) packages, as well as ggplot2 (Wickham, 2016) for data visualization. Data from one participant were excluded from the analysis of Experiment 1a due to a technical problem that occurred during the experiment. Data from one participant were excluded from the analysis of Experiment 1b due to performance at chance level in at least one of the conditions in the inattention part.

Reports of depth perception

The distributions of the three possible responses in each blur condition (i.e., blurry background and blurry figure) in

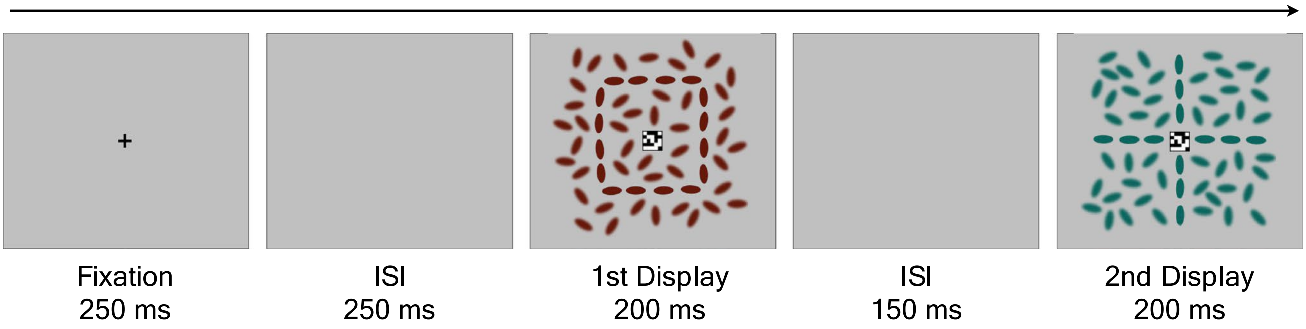

Fig. 2 The sequence of events in a trial. The illustration depicts an incongruent trial in the "blurred background" condition: the same target matrix (i.e., "same" target condition) appears on a backdrop that changes from a square to a cross (i.e., "different" backdrop organization condition). The background elements in both displays of the trial are blurry, while the figure elements are sharp. (Color figure online)

Experiments 1a–b are depicted in Fig. 3.[2] The percentage of each of the three responses in the two blur conditions was calculated for each participant. Pearson's chi-squared tests were conducted between the averaged distributions of responses in the two blur conditions. The tests showed no significant difference between the distributions in the different blur conditions, indicating no relevance to whether the sharp elements formed the figure or the background of the display, although these reports were less frequent for blurry figures in Experiment 1b compared with Experiment 1a, Experiment 1a: 68% and 77%, $\chi^2(2) = 0.36$, $p = .84$; Experiment 1b: 48% and 73%, $\chi^2(2) = 2.94$, $p = .23$.

These results show that depth perception was achieved in the displays, as sharp elements were perceived to be closer for the majority of the time. Importantly, this was despite the fact that no border could be used to imply occlusion and resolve the sign problem. Moreover, these results suggest that blur is more effective for assigning depth perception than figural status, as shown by the higher percentage of reports of blurry elements to be perceived in the background, while sharp elements were perceived in the front plane more often, similar to the results of Palmer and Brooks (2008). Yet, in that study, the only figural cue was ERG, whereas in the current study other figural cues could be identified, such as the smaller size of the figure compared with the background, and a coherent shape rather than a surface. Thus, our results further suggest that localizing objects in depth by figural assignment can be overrun by depth perception due to blurriness.

Inattention experiments

All RT summaries and analyses are based on participants' mean RTs for correct responses. Figure 3 depicts mean accuracy rates (ACs) and correct RTs in Experiments 1a–b for same and different targets as a function of background organization (same, different), and for the blur manipulation. Accuracy and RT data were each subjected to repeated-measures three-way analysis of variance (ANOVA: Target × Backdrop Organization × Blur Condition), for each experiment. RTs less than 250 ms and ± 2.5 standard deviations from condition mean for each participant were discarded (2.5% and 2.8% of trials in Experiment 1a and 1b, respectively). Bayes factors (BF_{10}) were calculated in addition to the frequentist hypothesis testing results to estimate the evidence for the H1 hypothesis in the data.

Experiment 1a: Shape by collinearity

The ANOVA showed a significant interaction between target and backdrop organization for the RT data, $F(1, 17) = 8.58$, $p = .01$, $\eta_p^2 = 0.34$, indicating congruency effects. No significant interaction was observed for accuracy, $F(1, 17) = 1.13$, $p = .30$, $\eta_p^2 = 0.06$. Planned comparisons showed that target-different judgments were faster (by 17 ms) when the backdrop organization changed than when it stayed the same, $t(1, 17) = 1.94$, $p = .04$, Cohen's $d = 0.48$, and same-target judgments were faster (by 25 ms) when the backdrop organization stayed the same than when it changed, $t(1, 17) = 2.41$, $p = .02$, Cohen's $d = 0.57$. Interestingly, a main effect of blur condition indicated that responses were more accurate (by 1.1%) when the blurry elements comprised the shape, compared with when they comprised the background, AC, $F(1, 17) = 5.46$, $p = .04$, $\eta_p^2 = 0.24$; RT, $F(1, 17) = 3.69$, $p = .07$, $\eta_p^2 = 0.18$. However, this effect was not modified by the other factors ($ps > 0.2$). The main effect of target was significant for accuracy, but not RT, showing that "same" responses were more accurate (by 3.8%) than "different" responses, AC, $F(1, 17) = 8.27$, $p = .02$, $\eta_p^2 = 0.33$; RT, $F < 1$. Bayes factor (BF_{10}) was estimated for models including the hypothesized interactions relative to the null hypothesis model of no effect. For the RT data, strong evidence was found for the model of the interaction between target and backdrop conditions ($BF_{10} = 10.78$), and anecdotal evidence for the null hypothesis was found for the three-way interaction with blur ($BF_{10} = 0.37$). For the accuracy data, Bayes factors showed anecdotal evidence for the null hypothesis ($BF_{10} = 0.33–0.38$) for both models. The most likely models under the H1 hypothesis included only the interaction between backdrop and target for RT ($BF_{10} = 9.67$), and only a main effect of target for accuracy ($BF_{10} = 5412.5$). Thus, congruency effects between target and backdrop conditions were found. These results suggest that the addition of blur to the displays facilitated the segmentation of the groups into shape and background under inattention.

Experiment 1b: Shape by color similarity

The interaction between target and backdrop conditions did not reach significance. Thus, no congruency effects were found. Interestingly, as in Experiment 1a, a main effect of blur condition was found on accuracy, AC, $F(1, 20) = 4.68$, $p = .04$, $\eta_p^2 = 0.19$; RT, $F < 1$; however, in this experiment, higher accuracy was found when the background was blurry (by 0.9%) compared with a blurry shape. This effect was not modified by the other factors ($ps > .20$). Bayes factor (BF_{10}) was estimated for models including the hypothesized interactions relative to the null hypothesis model of no effect. For both the accuracy and RT data, Bayes factors showed moderate evidence for the null hypothesis ($BF_{10} = 0.24–0.38$)

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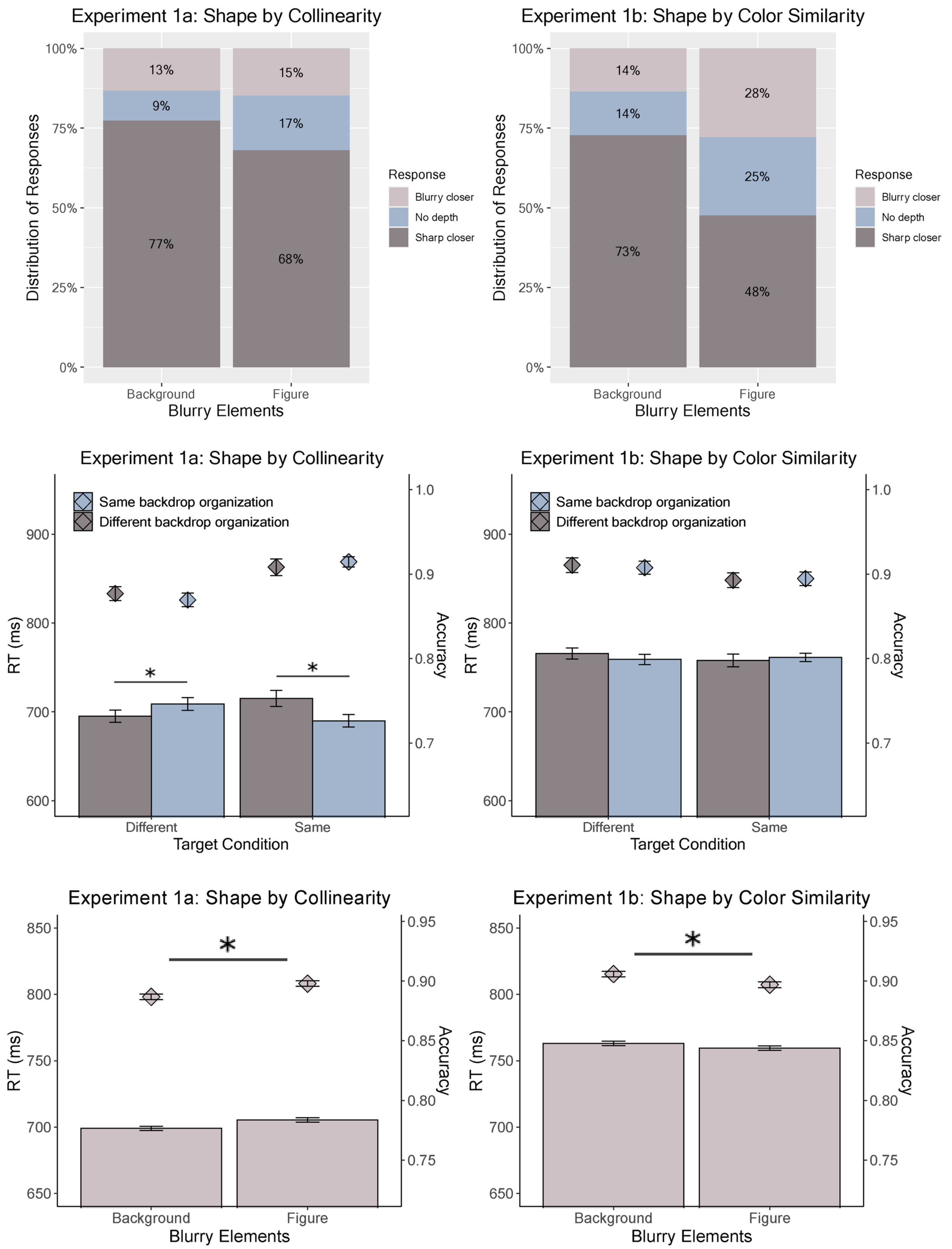
[2] As described in the Methods section, in Experiment 1a participants were asked about the perceived depth in the displays with a different question than in the other experiments. Thus, their responses were transformed to match the other format of the question that was used in the other five experiments, and the distribution of responses was calculated accordingly to allow a direct comparison.


Experiment 1a: Shape by Collinearity
Experiment 1b: Shape by Color Similarity
Distribution of Responses
100%
75%
50%
25%
0%
13%
9%
77%
15%
17%
68%
14%
14%
73%
28%
25%
48%
Response
Blurry closer
No depth
Sharp closer
Background
Figure
Blurry Elements
Experiment 1a: Shape by Collinearity
Experiment 1b: Shape by Color Similarity
Same backdrop organization
Different backdrop organization
RT (ms)
600
700
800
900
Accuracy
0.7
0.8
0.9
1.0
*
*
Different
Same
Target Condition
Experiment 1a: Shape by Collinearity
Experiment 1b: Shape by Color Similarity
RT (ms)
650
700
750
800
850
Accuracy
0.75
0.80
0.85
0.90
0.95
*
*
Background
Figure
Blurry Elements

◂**Fig. 3** Results of Experiments 1a (left) and 1b (right). Top: distributions of subjective reports indicating which group of elements (blurry/sharp) the observers perceived as closer (i.e., in front of the other elements. Middle: Mean accuracy (diamonds) and correct RTs (bars) for same and different targets as a function of backdrop organization (same, different). Bottom: Mean accuracy (diamonds) and correct RTs (bars) as a function of the blur condition (blurry background/figure elements). Error bars indicate within-subject standard errors as suggested by Cousineau (2005). *$p < .05$. ***$p < .001$

with the model including the two-way interaction between target and backdrop conditions, as well as the model including the three-way interaction of these factors with blur condition. The most likely models under the H1 hypothesis included only a main effect of target for accuracy ($\mathrm{BF}_{10} = 1.1$), and only the interaction between backdrop and target for RT ($\mathrm{BF}_{10} = 0.34$), as just mentioned, not indicating much evidence for the H1 hypothesis. Thus, adding blur to grouping organizations by color similarity did not facilitate the segmentation of the different groups into shape and background under inattention.

Surprise questions

The percentage of participants who responded correctly to the two surprise questions following the last experimental trial and the corresponding chi-squared tests are presented in Table 1. The percentage of participants who correctly reported the backdrop organization, as well as the percentage of participants who correctly reported whether the backdrop organization had changed on the preceding trial, were not significantly different from chance. These results confirmed that the backdrop organization was unattended. This pattern was repeated in the following experiments as well; thus, it will not be discussed for each of them individually for the sake of brevity.

The results of the inattention part in Experiments 1a–b show congruency effects between backdrop organization and the target matrix only for grouping of a shape due to collinearity, and not for a similar organization formed by color similarity. Importantly, a main effect of blur condition was found in both experiments, indicating that blur information was processed under inattention. The difference in results in the two experiments may stem from different demands for attention due to a competition over figural status (Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017a). In Experiment 1a, the background elements surrounding the shape were disorganized due to their random orientations, resulting in low (or no) competition over figural status between the shape and background. In contrast, in Experiment 1b, the background elements were organized into a cohesive group, which could have resulted in high competition over figural status between the groups. Thus, adding blur may have been enough to eliminate attentional demands in the first case, but not in the other. Alternatively, as attentional demands depend on the grouping cues and other processes involved in the organization (e.g., Kimchi, 2009; Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017a), it is possible that collinearity is a stronger cue than color similarity, thus showing a differential benefit from the addition of blur. In the following experiments, we chose to pursue this question by examining the same grouping cues, only in less complex grouping organizations, presumably reducing attentional demands that would allow blur to be more efficient.

Experiments 2a and 2b

The grouping organizations that were used in Experiments 1a–b depicted a shape that involve complex shape formation (Kimchi & Razpurker-Apfeld, 2004), which may have

Table 1 Percentage of participants who responded correctly to the forced-choice questions at the end of the inattention experiments in Experiments 1–3

	Correct reports and chi-squared tests			
	What was the organization in the backdrop?		*Was there a change the organization between displays in the last trial?*	
Experiment 1a	38% (7/18)	$\chi^2(1) = 0.14$ $p = .71$	44% (8/18)	$\chi^2(1) = .01$ $p = .96$
Experiment 1b	38% (8/21)	$\chi^2(1) = 0.48$ $p = .49$	43% (9/21)	$\chi^2(1) = 0.01$ $p = .95$
Experiment 2a	68% (13/19)	$\chi^2(1) = 1.13$ $p = .29$	32% (6/19)	$\chi^2(1) = 1.44$ $p = .23$
Experiment 2b	50% (15/30)	$\chi^2(1) = 0$ $p = 1$	53% (16/30)	$\chi^2(1) = 0$ $p = 1$
Experiment 3a	56% (18/32)	$\chi^2(1) = 0.01$ $p = .92$	34% (11/32)	$\chi^2(1) = 1.91$ $p = .17$
Experiment 3b	30% (7/23)	$\chi^2(1) = 0.48$ $p = .49$	52% (12/23)	$\chi^2(1) = 0.01$ $p = .99$

The results of the corresponding chi-squared tests for the difference from chance are reported with Yates correction.

contributed and increased attentional demands despite the addition of blur. In the following experiments, we presented participants with displays depicting grouping organizations of a single line formed by collinearity or color similarity. The latter was previously found to require attention (Kimchi & Razpurker-Apfeld, 2004), while the former has not been investigated under inattention yet. As before, blur was added to either one of the groups of elements. Because a main effect of blur condition was found in Experiments 1a–b, but its interactions with the other factors were not significant, in Experiment 2b, we allowed blur condition (i.e., blurry figure or blurry background) to change within a trial on half of the trials. This design, in which congruency effects may be directly affected by the blur manipulation, could potentially provide a more sensitive measure of the relationship between depth perception and attentional demands in grouping.

Methods

Participants

Twenty students from KU Leuven participated in Experiment 2a and 31 in Experiment 2b. All had normal or corrected-to-normal vision and normal color vision. None participated in more than one experiment, and all were naïve to the purpose of the study.

Stimuli

Experiment 2a: Line by collinearity Displays were similar to those used in Experiment 1a, except a subset of six elements was grouped by collinearity to form a horizontal or vertical line.

Experiment 2b: Line by color similarity Displays were similar to those used in Experiment 1b, except only 36 elements were used in a 6 × 6 matrix, and a subset of six elements was grouped by color similarity to form a horizontal or vertical line. Illustrations of the displays are presented in Fig. 4.

Design and procedure

The design and procedure were the same as in Experiments 1a–b, with the exception of a *blur-change* factor in the inattention part of Experiment 2b, where blur condition (background or figure) was administered independently from the other factors, resulting in half of the trials having the same blur condition in the two consecutive displays, while the other half had a different blur condition for each display. For example, if the line in the backdrop was blurry in the first display, in the second display either the line or the background could be blurry. With the new stimuli, the surprise questions at the end of the inattention part were adapted to ask about the orientation (horizontal/vertical) of the line in the display in the last trial rather than the identity of the shape.

Results and discussion

Data from one participant were excluded from the analysis of each experiment due to performance at chance level in at least one of the conditions in the inattention part of the experiment. Discarded RT outliers in the inattention experiment were 2.7% in Experiment 2a, and 3.3% in Experiment 2b.

Reports of depth perception

The distributions of reports are depicted in Fig. 5. Similar to the previous experiments, in Experiments 2a, the distributions were not significantly different for the two blur conditions, $\chi^2(2) = 4.27$, $p = .12$. However, in Experiment 2b, there was a significant difference between the two conditions, $\chi^2(2) = 6.57$, $p = .04$. Notably, when the background was blurry, sharp elements (i.e., figures) were perceived to be closer in the vast majority of trials (77% in Experiment 2a, and 72% in Experiment 2b). Yet, when the figures were blurry, sharp elements were reported to be closer less frequently (51% in Experiment 2a, and 43% in Experiment 2b). This suggests that depth perception for this organization was somewhat less stable. The implication of such instability in the corresponding inattention experiment should be minimal, where the analysis would show an interaction between all three factors, resulting in congruency effects only for sharp figures and not for blurry figures, if these organizations can be achieved under inattention.

Inattention experiments

Experiment 2a: Line by collinearity

Figure 5 depicts mean accuracy rates (ACs) and correct RTs in Experiments 2a–b for same and different targets as a function of background organization (same, different), and for the blur manipulation. Accuracy and RT data were each subjected to repeated-measures three-way analysis of variance (ANOVA: Target × Backdrop Organization × Blur Condition). The interaction between target and backdrop conditions did not reach significance, AC, $F < 1$; RT, $F(1, 18) = 1.58$, $p = .23$, $\eta_p^2 = 0.08$, thus, no congruency effects were found. The three-way interaction with blur was not significant either (Fs < 1). A significant main effect of target was found for RT, $F(1, 18) = 4.58$, $p = .05$, $\eta_p^2 = 0.20$, showing

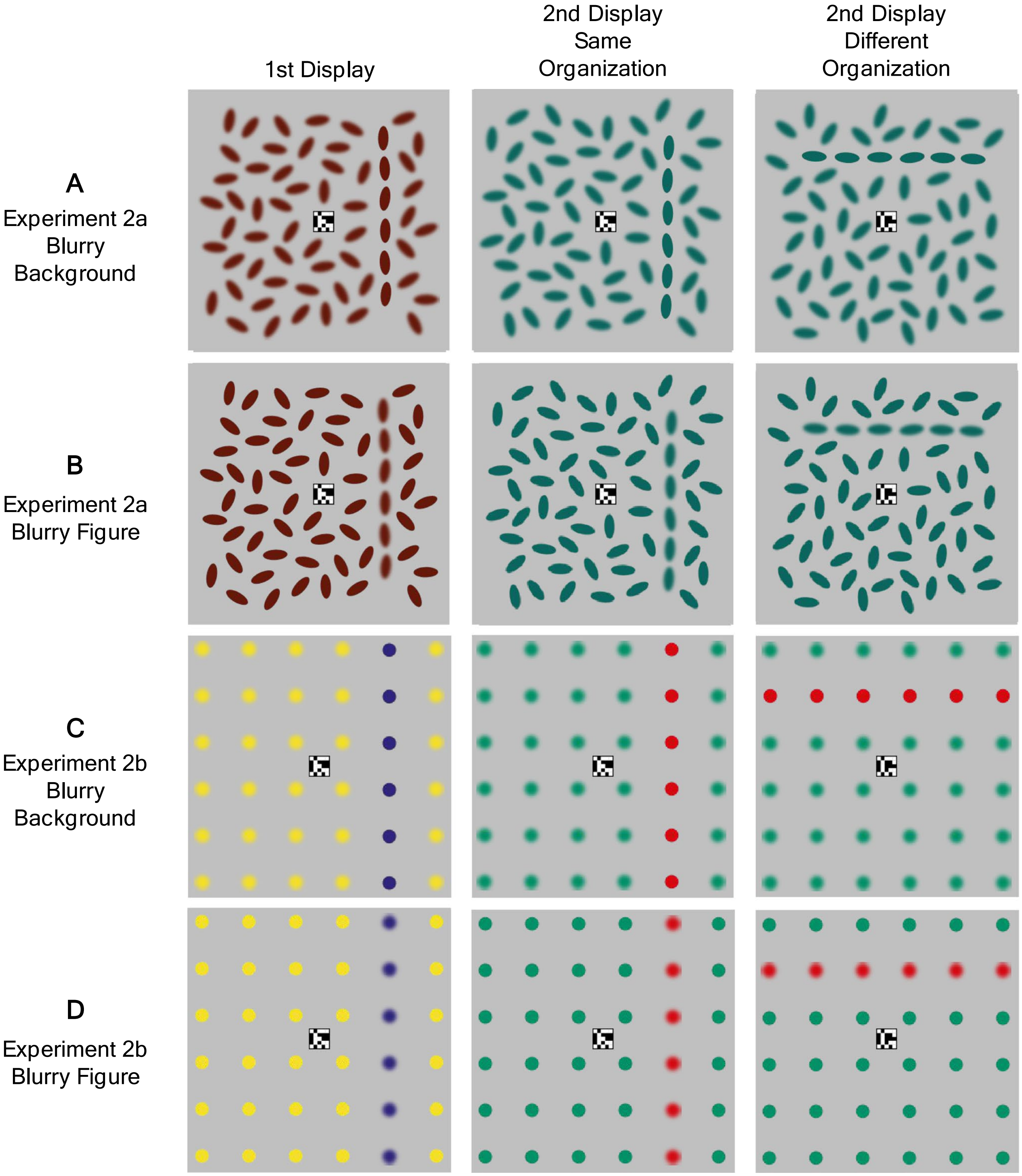
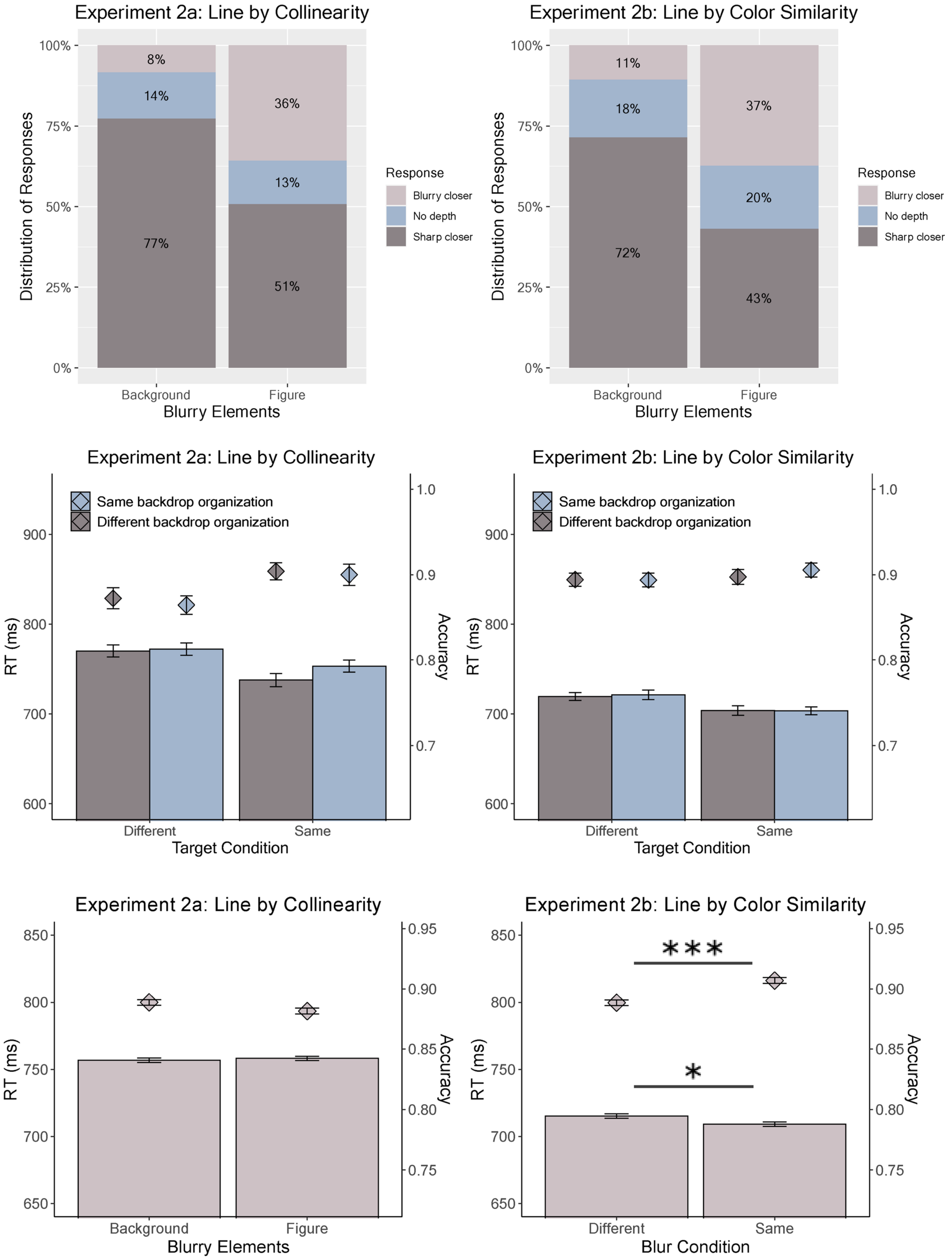


Fig. 4 Illustrations of the backdrop stimuli employed in Experiment 2a (collinearity grouping) and Experiment 2b (color similarity grouping). In half of the displays the background was blurry (**a** and **c**), and in the other half the figure was blurry (**b** and **d**). In Experiment 2b, on half of the trials blur condition could change within the two displays of one trial (i.e., from blurry background to blurry figure, and vice versa). See text for details. (Color figure online)


Experiment 2a: Line by Collinearity
Distribution of Responses
100%
75%
50%
25%
0%
8%
14%
77%
36%
13%
51%
Background
Figure
Blurry Elements
Response
Blurry closer
No depth
Sharp closer
Experiment 2b: Line by Color Similarity
11%
18%
72%
37%
20%
43%
Experiment 2a: Line by Collinearity
Same backdrop organization
Different backdrop organization
RT (ms)
Accuracy
900
800
700
600
1.0
0.9
0.8
0.7
Different
Same
Target Condition
Experiment 2b: Line by Color Similarity
Experiment 2a: Line by Collinearity
850
800
750
700
650
0.95
0.90
0.85
0.80
0.75
Background
Figure
Blurry Elements
Experiment 2b: Line by Color Similarity
***
*
Different
Same
Blur Condition

◂**Fig. 5** Results of Experiments 2a (left) and 2b (right). Top: distributions of subjective reports indicating which group of elements (blurry/sharp) the observers perceived as closer (i.e., in front of the other elements. Middle: Mean accuracy (diamonds) and correct RTs (bars) for same and different targets as a function of backdrop organization (same, different). Bottom: Mean accuracy (diamonds) and correct RTs (bars) as a function of the element blur condition in Experiment 2a (blurry background/figure elements), and blur change condition in Experiment 2b (same/different blur condition). Error bars indicate within-subject standard errors as suggested by Cousineau (2005). $^{*}p < .05$, $^{***}p < .001$

faster responses (by 26 ms) when there was no change in the target. This effect is known as the *fast–same effect* and is commonly found in studies that use a same–different judgment task (e.g., Farell, 1985). In contrast to Experiments 1a and 1b, the analysis showed no effect of blur condition (Fs ≤ 1). Again, this factor did not interact with any of the other two factors (ps > .16). Bayes factor (BF_{10}) was estimated for models including the hypothesized interactions relative to the null hypothesis model of no effect. For both the accuracy and RT data, Bayes factors showed moderate evidence for the null hypothesis (BF_{10} = 0.24–0.35) with the model including the two-way interaction between target and backdrop conditions, as well as the model including the three-way interaction of these factors with blur condition. The most likely models under the H1 hypothesis included only a main effect of target for both accuracy ($BF_{10} = 24.4$) and RT ($BF_{10} = 135$). Thus, blur did not facilitate the segmentation of groups into shape and background due to collinearity when the shape was one line.

Experiment 2b: Line by color similarity

In Experiment 2b we did not impose the constraint of blur condition being identical in both displays in a trial. Thus, on half of the trials, blur condition was different between the two displays, as the elements of the figure were blurry in one of the displays and the ground elements were blurry in the other. On the other half of the trials, blur condition was the same in the two displays, as blur was applied either to the elements of the figure or the elements of the ground in both. A three-way ANOVA (Blur Change × Target × Backdrop Organization) showed no significant interaction between target and backdrop conditions (Fs < 1). A significant main effect of blur change was found for both the accuracy and RT data, AC, $F(1, 29) = 8.25$, $p = .01$, $\eta_p^2 = 0.22$; RT, $F(1, 29) = 5.0$, $p = .03$, $\eta_p^2 = 0.15$, showing faster (by 6 ms) and more accurate (by 1.8%) responses when blur condition stayed the same between consecutive displays than when it changed. This factor showed only marginally significant interaction with target condition for accuracy, AC, $F(1, 29) = 3.04$, $p = .09$, $\eta_p^2 = 0.10$; RT, $F(1, 29) = 1.69$, $p = .20$, $\eta_p^2 = 0.06$. An inspection of the data revealed that this interaction was most probably due to slightly lower accuracy when both target and blur condition changed compared with the other three conditions. The main effect of target was marginally significant for RT, $F(1, 29) = 3.83$, $p = .06$, $\eta_p^2 = 0.12$, showing faster responses (by 17 ms) when the target stayed the same than when it changed. The three-way interaction between blur change, target, and backdrop conditions, was not significant (Fs < 1). As in the previous experiments, Bayes factor (BF_{10}) was estimated for models including the hypothesized interactions relative to the null hypothesis model of no effect. For both the accuracy and RT data, anecdotal to moderate evidence was found in favor of the null hypothesis (BF_{10} = 0.20–0.49). The most likely models under the H1 hypothesis included only a main effect of blur for accuracy ($BF_{10} = 2.1$), and only the main effect of target for RT ($BF_{10} = 201.6$).

The results of the subjective reports in Experiments 2a–b showed again that depth perception can be achieved in grouping organizations that include blur, without a border that could imply occlusion. However, the line figure seems to lead to a less stable depth perception, at least in the color similarity organizations that was used here. A possible explanation for this result is *sharpness overconstancy*, which is a phenomenon where a blurry edge is judged to be sharper when presented in the periphery of the visual field compared with foveal presentation (Galvin et al., 1997). It could be the case that in our color similarity displays, the blurriness of the lines was somewhat diminished due to their peripheral presentation. This may have led to a reduced efficiency of blur as a depth cue, which resulted in some depth ambiguity. Still, the general bias towards perceiving the sharp elements as closer was observed in that experiment as well.

With respect to the inattention experiments, this could not explain the lack of congruency effects. If depth was achieved and facilitated grouping but depth instability prevented this facilitation in that specific condition, it would have interfered with congruency effects when blur condition changed between displays in Experiment 2b. This should have resulted in an interaction between all three factors in that experiment; however, this interaction was not significant. Thus, the lack of congruency effects in these experiments suggests that the organizations were attentionally demanding, even when shape formation was simpler, and blur was added to the elements of one of the groups. Importantly, the difference in results between Experiment 1a and Experiment 2a indicates that the former were not simply caused by collinearity being a more powerful grouping cue than color similarity, otherwise adding blur to the collinearity displays depicting a line should have resulted in congruency effects, as the line presumably involved simpler shape formation, and thus, was less attentionally demanding. Interestingly, an effect of blur change was found in Experiment 2b, suggesting that blur information was processed under inattention.

Still, the representations for the organizations that were achieved due to the addition of blur were not strong enough to lead to congruency effects in this experiment.

Experiments 3a and 3b

So far, the results point to blur being an effective cue for depth perception when attention is available, as we observed with subjective reports. Still, it could be argued that the depth perception that was observed in Experiments 1–2 was possible because of the figure–ground organization provided by the collinearity or color similarity grouping cue. That is, blur information led to depth perception in these displays because a different cue for segmenting the groups of elements was available. Hence, in the last two experiments, we tested the effectiveness of blur when it is the only cue available in similar organizations to the ones we used before. We presented participants with displays containing grouping organizations of a cross and square (Experiment 3a), or of a horizontal and vertical line (Experiment 3b) by blur similarity. As before, we collected subjective reports of depth perception and used these displays as backdrop to the target matrix in an inattention experiment. We hypothesized that grouping by blur similarity would result in depth perception, as was found in the previous experiments, unless a blurry border is essential for depth perception in grouping in the absence of an additional grouping cue. In that case, subjective reports of no perceived depth would be more frequent than the other options. For the inattention part, since only little evidence for grouping being achieved under inattention was found with the addition of blur to another grouping cue, no congruency effects were predicted for blur similarity when presented alone. Still, as some processing of blur information was implied in the previous experiments, an effect of blur change might be observed, as this should not be affected by the presence or absence of another grouping cue in the display.

Methods

Participants

Thirty-two students from KU Leuven participated in Experiment 3a and 23 in Experiment 3b. All had normal or corrected-to-normal vision and normal color vision. None participated in more than one experiment, and all were naïve to the purpose of the study.

Stimuli, design, and procedure

Experiment 3a: Shape by blur similarity There were eight displays in total containing grouping organizations. The elements in each display were 48 circle elements, each 0.48° in diameter, spread at equal distances in a 7 × 7 matrix within a 9.1° × 9.1° area (the most central position contained a fixation cross). Each display contained elements in one color (blue or red; RGB 47, 37, 125, or 102, 25, 10, respectively). A subset of the elements in each display was blurry and formed a cross or a square (12 or 16 elements, respectively) while the rest of the elements were sharp, or vice versa.

Experiment 3b: Line by blur similarity Displays were similar to those used in Experiment 3a, except a subset of six elements was blurry to form a horizontal or vertical line while the rest were sharp, or vice versa. The design and procedure were the same as in Experiment 2b (including trials with mixed blur condition). Illustrations of the displays are presented in Fig. 6.

Results and discussion

Reports of depth perception

The distributions of responses in each blur condition (i.e., blurry background and blurry figure) are depicted in Fig. 7. Similar to Experiments 1a–b and 2a, in Experiment 3a, the difference between blur conditions was not significant, $\chi^2(2) = 1.70$, $p = .43$, showing that the majority of reports indicated sharp elements to be closer than blurry elements whether the blurry element formed the background (63%) or the figure (49%). However, in Experiment 3b, sharp elements were perceived as closer more frequently when blurry elements formed the background (68%), but when the figures were blurry, they were reported as being perceived closer more frequently (44%) than the sharp elements of the background (30%). These distributions were significantly different, $\chi^2(2) = 6.99$, $p = .03$. Generally, these results replicate those of the previous experiments, showing depth perception in grouping due to blur without an occlusion border, and a less stable depth perception of the peripheral blurry line figure, similar to what was found in Experiment 2b.

To understand better the nature of depth perception in our study, we analyzed the subjective reports further; First, to make sure that depth perception was equally achieved in all the conditions in the six experiments, we conducted a two-way mixed ANOVA on the mean proportions of “no-depth” responses, with blur conditions (figure/background) as within-subjects and experiment as between-subjects factors. Importantly, the analyses revealed no significant main effects or interaction, experiment: $F < 1$; blur condition: $F(1, 135) = 1.93$. $p = .34$; Experiment × Blur: $F < 1$, indicating that depth was equally perceived across experiments and conditions. Next, we were interested in possible effects of the specific grouping cue (collinearity/color-similarity/blur-similarity), organization (shape/line), and blur condition (figure/

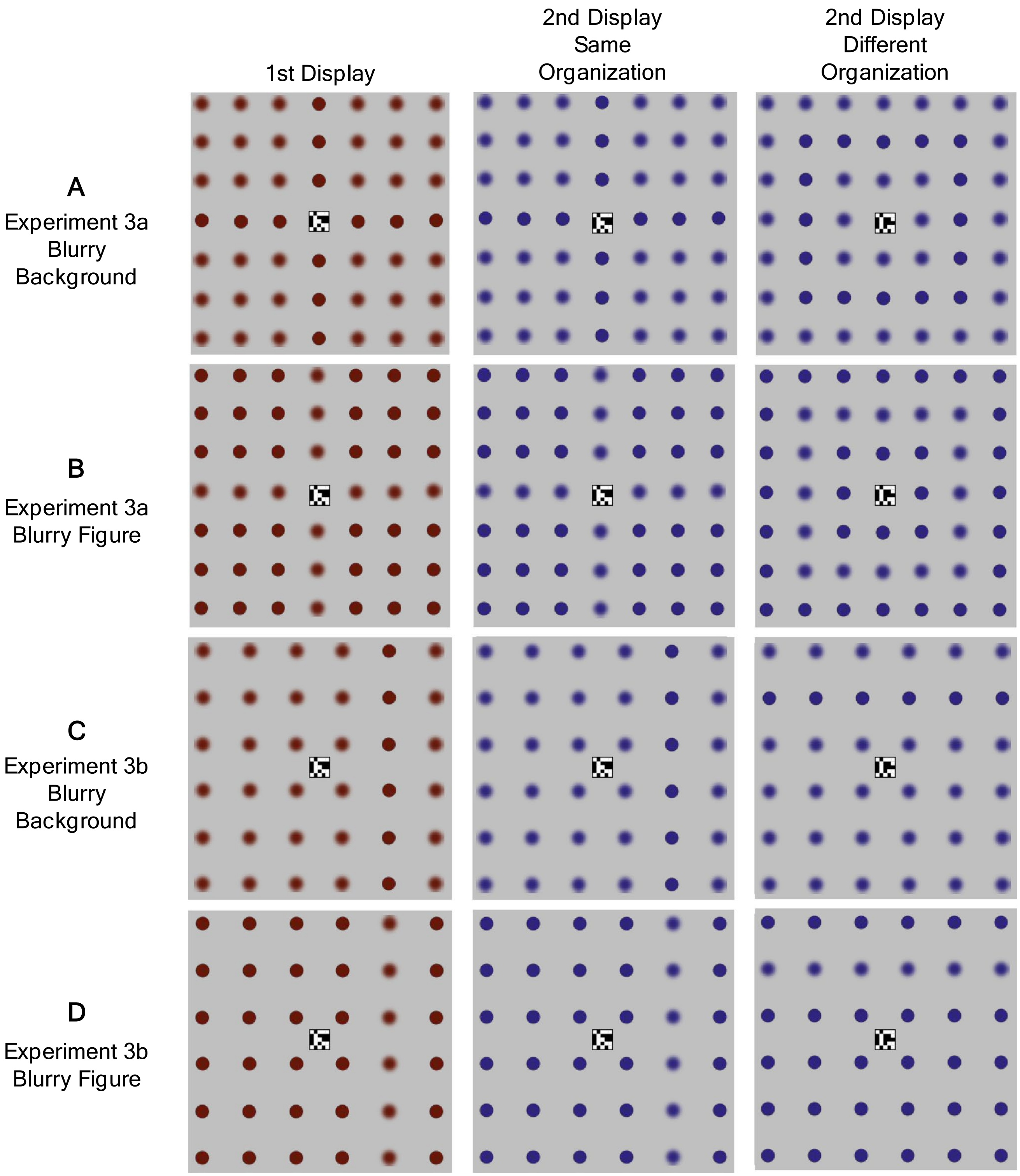
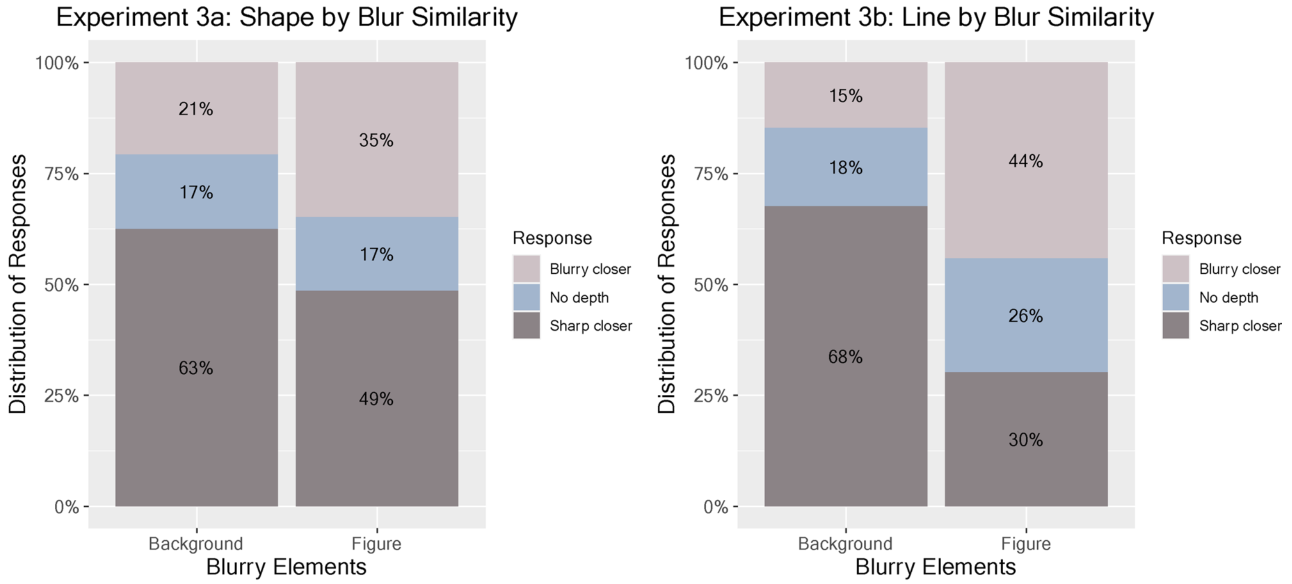
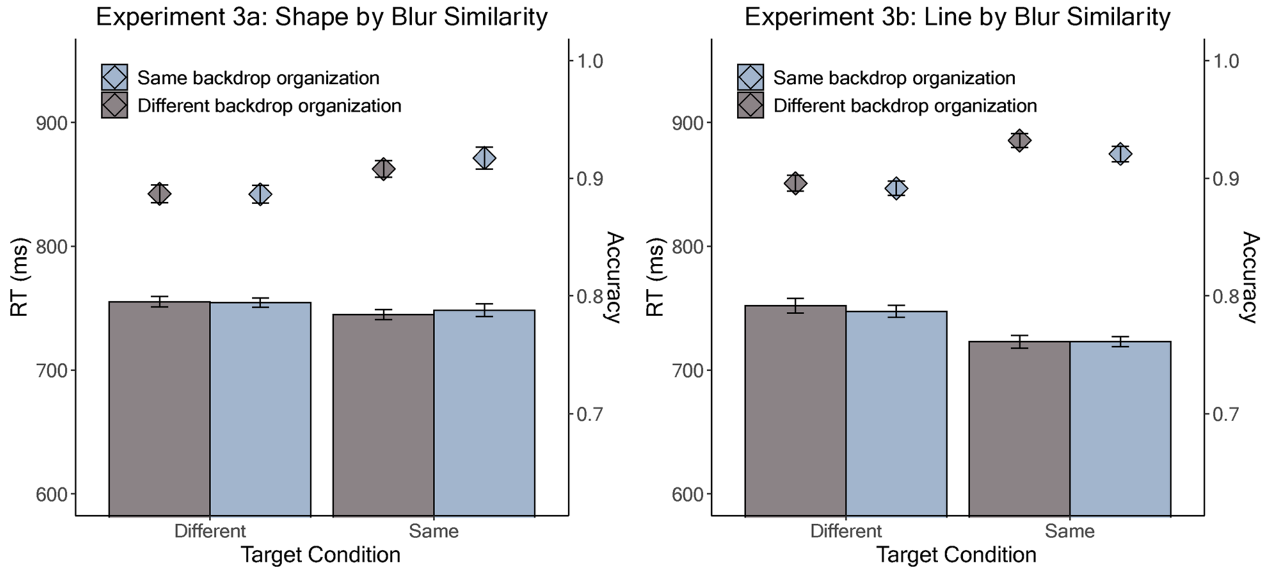
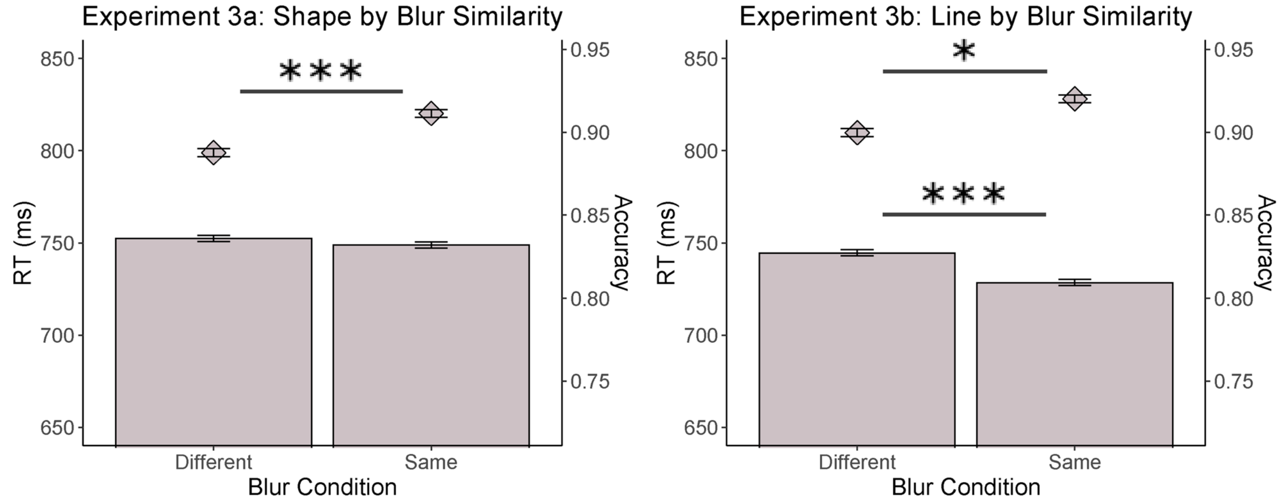


Fig. 6 Illustrations of the backdrop stimuli employed in Experiment 3a (shape) and Experiment 3b (line). On half of the trials, blur condition could change within the two displays of one trial (i.e., from blurry background to blurry figure, and vice versa). See text for details. (Color figure online)


Experiment 3a: Shape by Blur Similarity
Distribution of Responses
100%
75%
50%
25%
0%
21%
17%
63%
35%
17%
49%
Background
Figure
Blurry Elements
Response
Blurry closer
No depth
Sharp closer
Experiment 3b: Line by Blur Similarity
Distribution of Responses
100%
75%
50%
25%
0%
15%
18%
68%
44%
26%
30%
Background
Figure
Blurry Elements
Response
Blurry closer
No depth
Sharp closer


Experiment 3a: Shape by Blur Similarity
Same backdrop organization
Different backdrop organization
RT (ms)
900
800
700
600
Accuracy
1.0
0.9
0.8
0.7
Different
Same
Target Condition
Experiment 3b: Line by Blur Similarity
Same backdrop organization
Different backdrop organization
RT (ms)
900
800
700
600
Accuracy
1.0
0.9
0.8
0.7
Different
Same
Target Condition


Experiment 3a: Shape by Blur Similarity
***
RT (ms)
850
800
750
700
650
Accuracy
0.95
0.90
0.85
0.80
0.75
Different
Same
Blur Condition
Experiment 3b: Line by Blur Similarity
*
***
RT (ms)
850
800
750
700
650
Accuracy
0.95
0.90
0.85
0.80
0.75
Different
Same
Blur Condition

◂**Fig. 7** Results of Experiments 3a (left) and 3b (right). Top: distributions of subjective reports indicating which group of elements (blurry/sharp) the observers perceived as closer (i.e., in front of the other elements. Middle: Mean accuracy (diamonds) and correct RTs (bars) for same and different targets as a function of backdrop organization (same, different). Bottom: Mean accuracy (diamonds) and correct RTs (bars) as a function of blur change condition (same/different blur condition). Error bars indicate within-subject standard errors as suggested by Cousineau (2005). $*p < .05$. $***p < .001$

background) on reporting sharp elements or blurry elements closer. Due to the interdependency of these responses, a bias score was calculated, subtracting mean proportion of "blurry-closer" from "sharp-closer" responses for each participant in each condition. This bias score was subjected to a mixed ANOVA, with grouping cue and organization as between-subjects factors and blur condition as a within-subject factor. This analysis revealed a significant main effect of grouping cue, $F(2, 131) = 6.28$. $p = .01$, $\eta_p^2 = 0.09$. Pairwise *t* tests (two-tailed) using Holm's correction for multiple comparisons showed a significant difference only between collinearity and blur similarity, indicating a larger bias (by 24%) in reporting sharp elements as closer with grouping by collinearity ($p = .02$; ps = .16 for all other comparisons). This factor did not interact with the other factors, Fs < 1. A significant main effect of blur condition was found, $F(1, 131) = 59.68$, $p < .0001$, $\eta_p^2 = 0.31$, as well as a marginally significant main effect of organization, $F(1, 131) = 3.01$, $p = .09$, $\eta_p^2 = 0.02$. Importantly, these two factors showed a significant interaction, $F(1, 131) = 8.76$, $p = .01$, $\eta_p^2 = 0.06$. Two-sample *t* tests (two-tailed) using Holm's correction for multiple comparisons showed a significantly larger bias (by 21%) in reporting sharp elements as closer for blurry shapes than for blurry line organizations, $t(132.62) = 2.58$, $p = .02$, Cohen's $d = 0.44$, but no such difference was found when the blurry elements constructed the background of the display ($p = .48$). The latter suggests that blurry backgrounds are biased to be perceived in the back, while sharp figures are perceived in the front plane; however, blurry line figures lead to a less stable depth perception compared with blurry shape figures. These results confirm the observed difference in depth perception when line and shape figures are blurry, which was not observed for these organizations with a blurry background. In addition, the results indicate that collinearity grouping leads to a more biased depth perception of sharp elements as closer than blur similarity, regardless of the specific organization or blur condition, indicating a more stable depth perception in the former than in the latter.

Inattention experiments

Discarded RT outliers in the inattention experiment were 2.8% in Experiment 3a and 2.8% in Experiment 3b. Accuracy and RT data were each subjected to repeated-measures three-way analysis of variance (ANOVA: Blur Change × Target × Backdrop Organization), for each experiment.

Experiment 3a: Shape by blur similarity

Figure 7 depicts mean accuracy rates (ACs) and correct RTs in Experiments 3a–b for same and different targets as a function of background organization (same, different), and for the blur manipulation. The analysis showed no significant interaction between target and backdrop conditions (Fs < 1). A significant main effect of blur change was found for accuracy, AC, $F(1, 31) = 20.16$, $p < .0001$, $\eta_p^2 = 0.39$; RT, $F < 1$, showing more accurate responses (by 2.4%) when blur condition stayed the same within a trial than when it changed. This factor showed no significant interaction with target condition (Fs < 1). The main effect of target was marginally significant for accuracy, $F(1, 31) = 3.37$, $p = .08$, $\eta_p^2 = 0.10$, showing more accurate responses (by 2.6%) when the target stayed the same than when it changed. The three-way interaction between blur change, target and backdrop conditions was also not significant (Fs < 1). Bayes factor (BF_{10}) was estimated for models including the hypothesized interactions relative to the null hypothesis model of no effect. For both the accuracy and RT data, anecdotal to moderate evidence was found in favor of the null hypothesis (BF_{10} = 0.18–0.33). The most likely models under the H1 hypothesis included only main effects of target and blur change for accuracy ($BF_{10} = 361.9$), and only the main effect of target for RT ($BF_{10} = 0.69$). Thus, again, grouping organizations of a shape due to similarity by blur could not be achieved under inattention, although there was indication that blur information was processed to some extent.

Experiment 3b: Line by blur similarity

The analysis showed no significant interaction between target and backdrop conditions, Fs < 1. A significant main effect of blur change was found for RT and accuracy, AC, $F(1, 22) = 6.69$, $p = .02$, $\eta_p^2 = 0.23$; RT, $F(1, 22) = 18.92$, $p = .01$, $\eta_p^2 = 0.46$, showing faster (by 16 ms) and more accurate (by 2%) responses when blur condition stayed the same within a trial than when it changed. This factor showed no significant interaction with target condition, AC, $F < 1$; RT, $F(1, 22) = 1.8$, $p = .19$, $\eta_p^2 = 0.08$. The main effect of target was significant for accuracy and RT, AC, $F(1, 22) = 12.07$, $p = .002$, $\eta_p^2 = 0.35$; RT, $F(1, 22) = 10.97$, $p = .003$, $\eta_p^2 = 0.33$, showing faster (by 27 ms) and more accurate (by 3.3%) responses when the target stayed the same than when it changed. The three-way interaction between blur change, target and backdrop conditions was not significant, AC, $F(1, 22) = 1.08$, $p = .30$, $\eta_p^2 = 0.05$; RT, $F(1, 22) = 1.92$, $p = .18$, $\eta_p^2 = 0.08$. Bayes factor (BF_{10}) was estimated for models including the hypothesized interactions relative to the null hypothesis model of no effect. For both the accuracy and RT data, anecdotal to moderate evidence was found in favor of the null hypothesis ($BF_{10} = 0.23–0.36$). The most likely models under the H1 hypothesis included only main effects of target and blur change for both accuracy ($BF_{10} = 48382.3$) and RT ($BF_{10} = 5102875$).

In sum, the results of the inattention part in Experiments 3a–b showed no evidence of congruency effects for grouping by blur similarity under inattention. Still, a main effect of blur change condition was found in both experiments, suggesting that blur was processed under inattention to a point where a change in blur affected performance.

General discussion

The first goal of this study was to investigate depth perception in grouping organizations that contain blur as a depth cue. To that end, we presented grouping displays that included blurry elements that formed the figure or the background of the organization and collected subjective reports on the groups of elements (blurry/sharp) that the participants perceived as closer. We found that depth was obtained when blur was added to a grouping organization of a figure and background formed by collinearity (Experiments 1a and 2a) or color similarity (Experiments 1b and 2b), and when grouping was induced by blur similarity as a sole grouping cue (Experiments 3a–b). Importantly, sharp elements were perceived as closer the majority of the time, irrelevant of whether they formed the background or the figure, with the exception of the blurry lines in Experiment 3b. Previous research has suggested that the resolution of the sign problem in depth from blur is achieved by the grouping of a border with a surface according to their similarity in blur (e.g., Marshall et al., 1996; Mather, 1996; Palmer & Brooks, 2008). However, we provide here new evidence for the efficiency of blur as a depth cue in grouping organizations that do not include borders between surfaces. That is, no occlusion was implied in these organizations to allow the inference for the relative depth of the elements in the displays. O'Shea et al. (1997) showed that depth perception of gratings and textures with a shared sharp border depended on their relative blur—the blurrier texture was consistently judged to be farther away than the less blurry one. The general pattern of results found in the current study showed that when no border is present, blurry groups are perceived to be in the back and sharp groups to be in the front. That is to say, occlusion edge blur may be effective only when it is attached to a blurry texture, presumably to overcome an inherent bias to perceive blurry textures as farther.

The second goal of this study was to examine whether attentional demands in perceptual grouping can be alleviated by the addition of blur. To that end, we used the inattention paradigm with an online measure (Driver et al., 2001; Kimchi & Peterson, 2008; Kimchi & Razpurker-Apfeld, 2004; Rashal et al., 2017a; Russell & Driver, 2005). We hypothesized that adding blur to grouping organizations constructed by other grouping cues could lead to a diminished demand for attentional resources if the different groups of elements were perceived on different depth planes, potentially facilitating figure–ground segmentation. We found little evidence that attentional demands were diminished in our study, as congruency effects between the target matrix and the backdrop organization were only found when blur was added to an organization of a shape grouped by collinearity (Experiment 1a). No congruency effects were found for a similar organization constructed by color similarity (Experiment 1b), or when difficulty of shape formation was reduced by presenting a straight line as the figure with the same grouping cues (Experiments 2a–b). Not surprisingly, no congruency effects emerged when similar organizations were constructed by blur similarity as a sole grouping cue (Experiments 3a–b). These results indicate that these organizations were not achieved under inattention when blur was added.

Interestingly, a main effect of the blur manipulation was found in five out of our six experiments, indicating that at least some information about blur was processed under inattention. In particular, in Experiments 2b and 3a–b we introduced a blur-change condition, where the blur condition (figure/background) changed within displays of a trial, which resulted in worse performance in the task when a change in blur condition occurred in the backdrop displays. The effect of blur-change might be explained by the changing amount of blur in the different organizations, as the figures were composed of less elements than the backgrounds. Hence, if the amount of blur is represented under inattention, a change in blur condition would be processed as well. However, this does not explain the effects of the blur manipulation in Experiments 1a–b, where blur condition was always the same within a trial, and the opposite directionality of the effect in the two experiments. In this case, it could be argued that depth perception was achieved under inattention, but not grouping. That is, blurry elements could have been perceived on one depth plane and sharp elements on another, resulting in some interference to the task, perhaps grouping the target with one group of elements on the same depth plane and leading to better performance in that condition. Alternatively, the amount of blur in the display may have led to better segmentation of the target from the surrounding backdrop in some cases due to its high spatial frequency. Specifically, a blurry background might enhance performance as it contains more lower frequencies than a background formed by sharp elements and a blurry figure. An examination of the blur condition effect (figure/background) in Experiments 2b and 3a–b in trials where blur condition stayed the same within a trial (i.e., excluding trials where blur-change condition was different), revealed that, similar to the effect in Experiment 1b, accuracy in the task was consistently higher (~2%) when the background was blurry compared with a blurry figure ($ps < .02$). The opposite effect found in Experiment 1a may have resulted from the specific arrangement of elements in the displays of that experiment.

The results of Experiment 1a suggest that grouping of a shape by collinearity could benefit from the addition of blur to one of the groups. This was probably not due to reduced competition over figural assignment, since no congruency effects were found in Experiment 2a, where a collinear line was presented surrounded by randomly oriented elements. In the latter, reduced attentional demands due to reduced shape complexity are also assumed (Kimchi & Razpurker-Apfeld, 2004). Thus, a possible explanation for this result would be the more consistent depth perception that was found in Experiment 1a compared with the other experiments with the subjective reports. Presumably, the more stable representation of depth led to a more consistent segmentation of the groups of elements, thus, leading to better representations of the organizations under inattention. Alternatively, it is possible that the organizations in Experiment 1a were stronger than the ones in the other experiments. Several studies attempted to address the question of grouping strength (e.g., Claessens & Wagemans, 2005; Hochberg & Hardy, 1960; Hochberg & Silverstein, 1956; Kubovy & van den Berg, 2008; Montoro et al., 2017; Quinlan & Wilton, 1998; Schmidt & Schmidt, 2013). However, inconsistent findings and an apparent dissociation between direct and indirect measures of grouping (e.g., Schmidt & Schmidt, 2013) suggest a flexible mechanism that considers the combination of all available organizational cues (Rashal et al., 2017b). Since the strength of the organizations that were employed in this study was not examined directly, we can only infer from the results presented here (i.e., a more stable depth perception and the ability to be achieved under inattention), that the organizations in Experiment 1a may have had stronger representations than the organizations in the other experiments.

The effectiveness of blur as a depth cue has been debated previously. For example, Held et al. (2012) argued that blur is complementary to disparity, blur being more effective at distances far from fixation while disparity dominates at fixation. However, Langer and Siciliano (2015), using similar displays to those of Held et al. (2012), showed that depth perception was similar when disparity was manipulated alone or in combination with blur. Moreover, blur alone was not effective for depth perception in large disparities—that is, far from fixation. One of the reasons Langer and Siciliano (2015) pointed out for the differences between these studies is the mode of presentation. Held et al. (2012) used a volumetric stereo display that allowed natural defocus blur to emerge (Love et al., 2009), whereas in Langer and Siciliano (2015) depth was achieved in a traditional stereo display and blur was rendered artificially. Hence, blur might be (more) effective for depth perception when combined with other optical cues such as accommodation, color aberration and more (for an extensive discussion see Langer & Siciliano, 2015). Recently, Zannoli et al. (2016) examined the efficiency of defocus and rendered blur, by presenting participants with textures on single or multiple planes in a depth ordering task. In the single-plane condition, blur was rendered to simulate defocus blur, as if the participant was focusing on one of the textures. In the multiple-plane condition, the participant focused on one of the textures, resulting in real defocus blur. Their results showed that judgements of depth ordering were more accurate in the multiple-plane condition, where physical defocus was present, compared with the single-plane condition, where defocus blur was simulated. Since in our study we used rendered blur for elements that were presented on a two-dimensional surface, this might have hindered potential effects in the inattention experiments. Presenting the displays in stereoscopic viewing may show different results.

To conclude, the relationship between depth perception, attention, and perceptual organization is a complex and dynamic cooperation between physical and psychological factors. Previous studies have demonstrated evidence in support of attention operating in three-dimensional space, and the iterative and multistage nature of organizational processes in relation to attention and depth. The current study provides new evidence of depth perception from blur in grouping organizations without implied occlusion from grouping of a border and surface elements. In addition, evidence was found for the processing of blur information under inattention; however, only little evidence was found in favor of a beneficial effect of depth from blur on attentional requirements in grouping.

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Open practices statement

Data or materials for the experiments reported here is available upon request. None of the experiments was preregistered.