The Role of Hue in Visual Search for Texture Differences: Implications for Camouflage Design

Geoffrey W. Stuart, Dominic Yip and Hinze Hogendoorn

Melbourne School of Psychological Sciences

Faculty of Medicine, Dentistry and Health Sciences

The University of Melbourne, Australia

Abstract

The purpose of camouflage is to be inconspicuous against a given background. Colour is an important component of camouflage, and the task of designing a single camouflage pattern for use against multiple different backgrounds is particularly challenging. As it is impossible to match the colour gamut of each background exactly, the question arises which colours from the different backgrounds should be incorporated in a camouflage pattern to achieve optimal concealment. Here, we used a visual search paradigm to address this question. Observers searched multi-coloured continuous textures for target regions defined by either the presence or absence of additional hues. Targets could be either a combination of five hues against a four-hued background ("patches"), or a combination of four hues against a five-hued background ("holes"). In Experiment 1, a search asymmetry was observed for the different targets, as observers were less accurate and slower at detecting holes than patches. Additionally, we observed a linear separability effect: search for a target was more difficult when the hue that defined the target was within the gamut of distractor colours (e.g. orange amongst reds and yellows). In Experiment 2, we further investigated "hole" targets designed for two different backgrounds and found that optimal concealment against *both* backgrounds was achieved by including intermediate colours that represented a compromise between the common colours and the unique colours of each background. The findings provide insights into how search asymmetries can be extended to complex texture properties and help inform the design process of camouflage for multiple backgrounds.

Introduction

What makes an object stand out from its background? This is a question that is not only of theoretical interest, but also has important practical implications. Sometimes an object needs to be highly conspicuous, such as a safety warning sign. In other circumstances the object should be as inconspicuous as possible, as when the object is camouflaged. In the natural world, animals use various strategies to make themselves less visible to predators or to their prey, or to disguise their identity through mimicry or distractive markings (Cott, 1940; see Cuthill, 2019 for a comprehensive review). In order to blend visually into the background an animal may use two non-exclusive strategies, background matching and boundary disruption. The latter strategy comes into play because even though the surface of the animal may match the background, its outline may still be apparent. In disruptive camouflage, distinctive markings on the animal's body break up its outline so that the form of the animal is masked (e.g., Stevens, Cuthill, Windsor and Walker, 2006). Disruptive camouflage can work in concert with, or independently of, background matching (Schaefer and Stobbe, 2006; Troscianko, Skelhorn and Stevens, 2018).

Most military camouflage is designed to render the camouflaged object less visible by matching the object surface to the background, and secondarily by disrupting the visual outline of the object. While the latter strategy is an important element of camouflage, the present study is solely concerned with specific aspects of human visual perception relevant to background matching camouflage, in particular the discriminability of multi-coloured textures. Both natural and artificial background matching camouflage patterns can be viewed as visual textures, the pattern and colour of which minimises contrast with the background. It is now well established that texture differences contribute to figure-ground contrast. Parkhurst and Neibur (2004) showed that in a natural scene, texture differences alone suffice for visual contrast.

Texture contrast has two major components. The first is pattern. This has been the subject of extensive research, starting with the pioneering research of Julesz (1981; for a recent review see Victor, Conte and Chubb, 2017). This research has largely used black and white or greyscale textures, often artificially constructed from simple geometrical elements. More recent research has considered the statistical properties of natural textures (Portilla and Simoncelli, 2000; Balas, 2006; Freeman et al., 2013). The colour composition of textures is also important but has received little research attention. If the surface texture of an object is of a different overall lightness, hue or saturation compared to the background it will stand out, even if the texture pattern is the same. Where colour has been considered in the context of texture perception, it has usually been treated as an additional or competing cue, rather than as an inherent property of the texture combined with its pattern (Terzic, Krishna and DeBouf, 2017; Zhang, Lang and Luo, 2017).

The design of a camouflage texture to be used against a single textured background does not require any theory of texture perception. A continuous, natural looking texture can be produced from a sample patch using a variety of texture synthesis algorithms (Akl et al., 2018). A challenge arises when considering how to optimise a camouflage pattern for use against more than one background. This was exemplified by the case of the "universal camouflage pattern" designed for the U.S. Army (Dugas et al., 2004), which proved to be ineffective in the field and following re-evaluation (Anonymous, 2009) had to be urgently replaced with a pattern more suited to a particular operating environment. One probable reason was that the colour gamut of the "universal" camouflage uniform was too different from that of natural environments, lacking both brown and black texture elements. Arguably, a cause of this design failure was a lack of fundamental theory to inform the design of a general-purpose camouflage, or to specify the limits at which such camouflage would lose effectiveness against any of the backgrounds.

Consider the problem of choosing the colours to be used in a general-purpose camouflage texture. Unless the colour gamut of the different backgrounds is exactly the same, no single texture will match more than one background perfectly. Assume that in the simplest case of two backgrounds, each background contains a colour that is not present in the other. Should the average texture contain the complete range of colours, or should it contain only the colours common to both backgrounds? Perhaps the unique colours should be attenuated so that they assist a camouflage's effectiveness against one of the backgrounds but do not cause it to stand out too much against the other.

From the perspective of natural camouflage, Hughes, Liggins and Stevens (2019) noted that many animals live in heterogenous environments, or their environment may change with the seasons, so a strategy of perfectly matching a particular visual environment may not be optimal. If blending camouflage is the chosen strategy (rather than mimicry or other strategies) they argued that a generalist or compromise camouflage may be most effective, where the camouflage matches several backgrounds approximately, but none of them exactly. They considered both pattern and colour cues, and suggested that intermediate patterns and colours may represent the best compromise between different backgrounds. Insights from nature are complicated because natural camouflage evolves under a number of selective pressures. For example, Merilaita, Lyttinen and Mappes (2001) have argued that as well as background characteristics, a compromise camouflage will be influenced by the time spent in two or more visual environments during foraging, and the presence of predators in those environments. There may also be competing selective pressures on natural camouflage, for instance the requirement to attract mates through visual display. For these reasons it is not straightforward to predict the colours to be used to optimise an isolated aspect of camouflage, such as the colour composition of a texture (holding texture pattern and edge disruption constant), from studies of natural camouflage. This is especially the case considering that most animals have very different colour vision to humans. Indeed, Hughes, Liggins and Stevens (2019) concluded that the question of compromise camouflage requires an interdisciplinary approach, including the use of laboratory studies to test the predictions of theoretical models. This is the approach taken here.

The current texture perception literature has not addressed the question of how colour composition affects the discriminability of multicoloured textures. However, some theoretical insights can be gained from the literature on visual search for single-coloured targets among distractors. A key finding was made by D'Zmura (1991), who found that if the colour of a target was in between that of heterogenous distractors, for example an orange target among red and yellow distractors, it was more difficult to find than a red target among orange and yellow distractors. This theory of linear separability was developed further by Bauer and colleagues (Bauer, Jolicouer and Cowan, 1996). Subsequently Vigneshvel and Arun (2010) argued that the findings of Bauer and colleagues might be explained purely in terms of target to distractor perceptual distances, without the need to invoke the idea of linear separability. However, Vigneshvel and Arun themselves did not use coloured targets and distractors. Citing the work of Lindsey et al. (2010), they asserted that perceptual distances, as defined by colour differences in uniform colour space, did not correspond to distances in "search space", defined by pairwise search times. There are two reasons why this assertion may not hold. Lindsey et al. (2010) defined their stimuli in CIELAB colour space. This is an approximately uniform space, but Kuehni (1998) demonstrated that it was far from uniform compared to Munsell colour space[1]. In

[1] Note that even the best colour spaces are not uniform in the sense that a vector of constant length, in any direction in the three-dimensional space, represents a constant supra-threshold colour difference. Uniformity only holds

addition, Lindsey et al (2010) only manipulated the saturation of targets and distractors, keeping hue constant. On the other hand, Bauer and colleagues studied linear separability in two-dimensional CIELUV colour space, another approximately uniform space (Melgosa, Quesida and Hita, 1994), keeping only luminance constant. That is, targets and distractors did not lie on a hue circle of constant saturation. This meant that sometimes a target colour could differ in saturation as well as hue from distractors, and saturation itself can provide the basis for selective attention (Lindsey et al., 2010; Stuart, Barsdell and Day, 2014), complicating the interpretation of these findings.

Another relevant finding from the literature on visual search is that of search asymmetry (Wolfe, 2001). There are good reasons to anticipate that search for a texture patch that has an additional colour compared to a textured background will be more efficient than search for a patch that lacks one of the colours of the background texture. Bruce et al. (2015) identified two major types of search asymmetry. The first type of asymmetry involves search for targets that are defined by the presence or absence of a feature, such as the search for the letter Q amongst Os, or vice versa (Treisman and Gormican, 1988). The letter Q contains a unique feature and is easier to find amongst a background of Os than a letter O amongst Qs, which is defined by the lack of a feature. In the case of multicoloured textures, a patch containing an additional colour may be easier to find than a patch lacking one of the colours of the background.

A second type of search asymmetry is observed in the case of single feature targets when the roles of target and distractor are exchanged. For example, search for a tilted line segment among vertical distractors is easier than search for a vertical line segment among tilted distractors. Vincent (2011) argued that this type of asymmetry may be due to the fact that the tilted distractors produce a noisier background due to a greater perceptual sensitivity to departures from the cardinal horizontal and vertical directions. Extending this logic, a texture background composed of more colours than a target patch may impede search efficiency more than a background composed of fewer colours than a target patch. This proposition is supported by studies of asymmetry in texture segregation, again appealing to the idea that some textures are inherently noisier than others (Rubenstein and Sagi, 1990; Potechin and Gurnsey, 2006).

---

locally within the dimensions of lightness, hue and saturation. Human vision is much more sensitive to hue differences than differences in lightness or saturation. At any given point in uniform colour space, three-dimensional ellipsoids define surfaces of constant perceptual differences (Morillas and Fairchild, 2018), and these cannot be "packed" into a Euclidean space.

Rosenholtz (2001) has pointed out that any claim for search asymmetry is dependent on the perceptual uniformity of the feature space. Given non-uniformity of the colour spaces used in previous studies, the present study will use a carefully calibrated set of uniformly spaced colours that differ only in hue: Teufel colours (Teufel and Wehrehan, 2000). To control for the effect of pattern, in the experiments we will use exactly the same texture pattern in all conditions, only manipulating the colour composition of the texture. The textures are irregular Voronoi textures constrained so that there are no direct neighbouring elements of the same colour. This is to prevent the formation of larger elements of the same colour that would provide a pattern cue to the presence of a target in textures containing different numbers of colours. Figure 1 shows an example of the textures used in the experiments. The irregularity of the pattern is used to mask boundary cues that might arise in a regular (e.g., hexagonal) array due to a circular grouping of elements along the boundary of a target patch.

In this study, we address two questions directly relevant to the design of a camouflage pattern intended for use on multiple backgrounds. 1. Is the ease of search for a multicoloured texture patch a function of the linear separability of the unique colour defining that patch against the background? 2. Is a texture patch containing an additional colour more conspicuous than a texture patch lacking a colour, relative to the background?

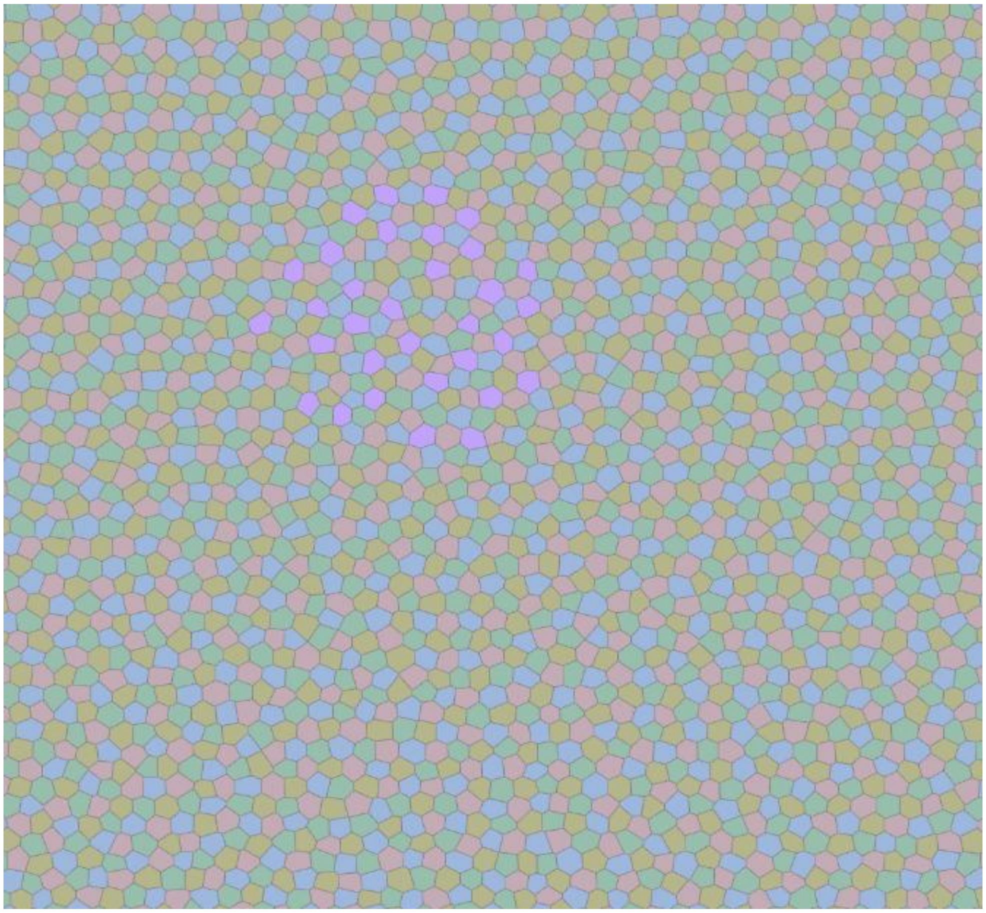


Figure 1. Example of a multicoloured texture used in the present study, with a target patch created by adding one in five elements of a different colour to a four-colour background. A highly separable colour has been used for illustration.

General Methods

Participants

Participants were recruited from the Melbourne School of Psychological Sciences' reimbursed participant panel. All participants had normal or corrected-to-normal vision and normal colour vision, as assessed with Ishihara pseudo-isochromatic plates. All participants were briefed via a plain language statement and provided their informed consent in accordance with the declaration of Helsinki. The study was approved by the University of Melbourne Human Ethics Advisory Group.

Apparatus

Stimuli were presented on a Sony GDM-17SEII CRT monitor driven by an AMD Radeon HD 5450 graphics card. The refresh rate of the monitor was set to 75 Hz with a resolution of 1280 x 1024. A Minolta CS100A colorimeter was used to measure the chromaticity coordinates of the red, green and blue phosphors in CIE 1931 (x, y) colour space. The colours were specified with 8-bit accuracy. Participants' viewing distance was standardized at 65cm with the use of a chinrest. Participants viewed the visual display in a dimly lit room through a 1024 pixel square aperture in a white card, and entered their responses with mouse clicks on a computer mouse. The computer mouse was connected to a Dell OptiPlex 990 computer running Matlab R2017b (The MathWorks, Natick, MA) with PsychToolbox 3.0.12 extensions (Brainard, 1997).

Stimuli

Voronoi texture

The textures used as the basis for the experiments were irregular Voronoi textures of 1024 pixels / 19.46 deg square. The most important property of these textures is that they can be held constant while being rendered with varying numbers of colours (unlike say, Fourier textures, or typical camouflage patterns based on overlapping irregular shapes). With some additional constraints, this can be done without changing the size or shape of the texture elements, so that discrimination has to be on the basis of colour composition, not some associated artefact. The particular Voronoi textures we constructed are based on a noisy hexagonal array. This spatial noise produces a more natural looking texture and masks any form cues (such as a circular arrangement of added colours) that might reveal the presence of the target. As every texture element has a boundary, there are no edges defining the target.

Irregular Voronoi textures were constructed by first creating a regular hexagonal grid. The spacing between the points on the grid were set to 24 pixels, which represented 27.36 minutes of arc. Single tiles within the base texture were filled with one of four Teufel colours selected according to the experimental design. The colours of the single tiles were not chosen completely at random because in that case, neighbouring tiles could have the same colour (Figure 2; left panel). This would otherwise have allowed larger elements composed of neighbouring elements of the same colour to serve as an indication as to the number of colours in the texture. Therefore, the colours of the single tiles were chosen at random but under the condition that a given tile could have no neighbouring tile of the same colour (Figure 2; middle panel). To allow the Voronoi pattern to be more irregular, and to disrupt the initially circular boundaries of the targets, the points on the hexagonal grid were randomly jittered by 6.16 minutes of arc in a random direction. This produced an irregular base texture template that comprised four Teufel colours (Figure 2; right panel).

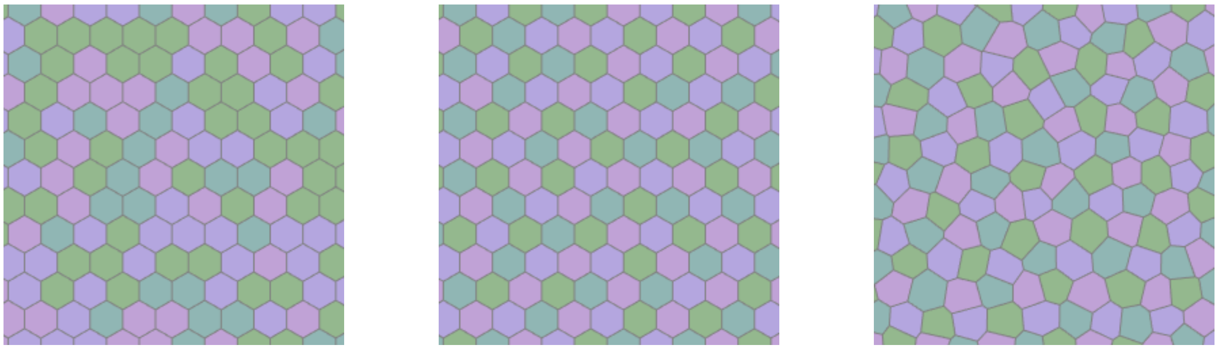


Figure 2. Example of Voronoi texture construction. The left panel demonstrates a regular texture with random Teufel colours. The middle panel demonstrates a regular texture with no identical adjacent colours. The right panel demonstrates an irregular texture with no identical adjacent colours. This panel represents the final four-coloured base texture used in the present study.

In the first experiment, a target was defined by the presence of a five-coloured region of texture on a four-coloured background (therefore producing a “patch”), or a four-coloured region of texture on a five-coloured background (producing a “hole”). In both conditions, a fifth colour defined the region as either a patch or a hole. This was achieved by constructing a separate five-colour texture, also with the condition that single tiles have no identical adjacent colours. The positions of all tiles designated to be the fifth colour were extracted from this second texture and overlaid onto the original four-coloured base texture. If the target was defined as a patch, only the tiles *within* the target position and the radius were overlaid on the four-coloured texture (Figure 3; top left panel). If the target was defined as a hole, only the tiles *outside* the target position and radius were overlaid on the four-coloured texture (Figure 3; top right panel). For catch trials, the initial four-coloured texture was left unmodified or all of the fifth colour texture elements were overlaid (Figure 3, bottom panels).

In all target-present stimuli, the position of the target was randomly selected in a circular donut arrangement so that the target could never appear in either of the four corners. This was achieved by making the inner edge of the target to be a minimum of 57 min of arc from the centre of the display and also making the outer boundary of the target at least 71 min of arc from the edge of the display.

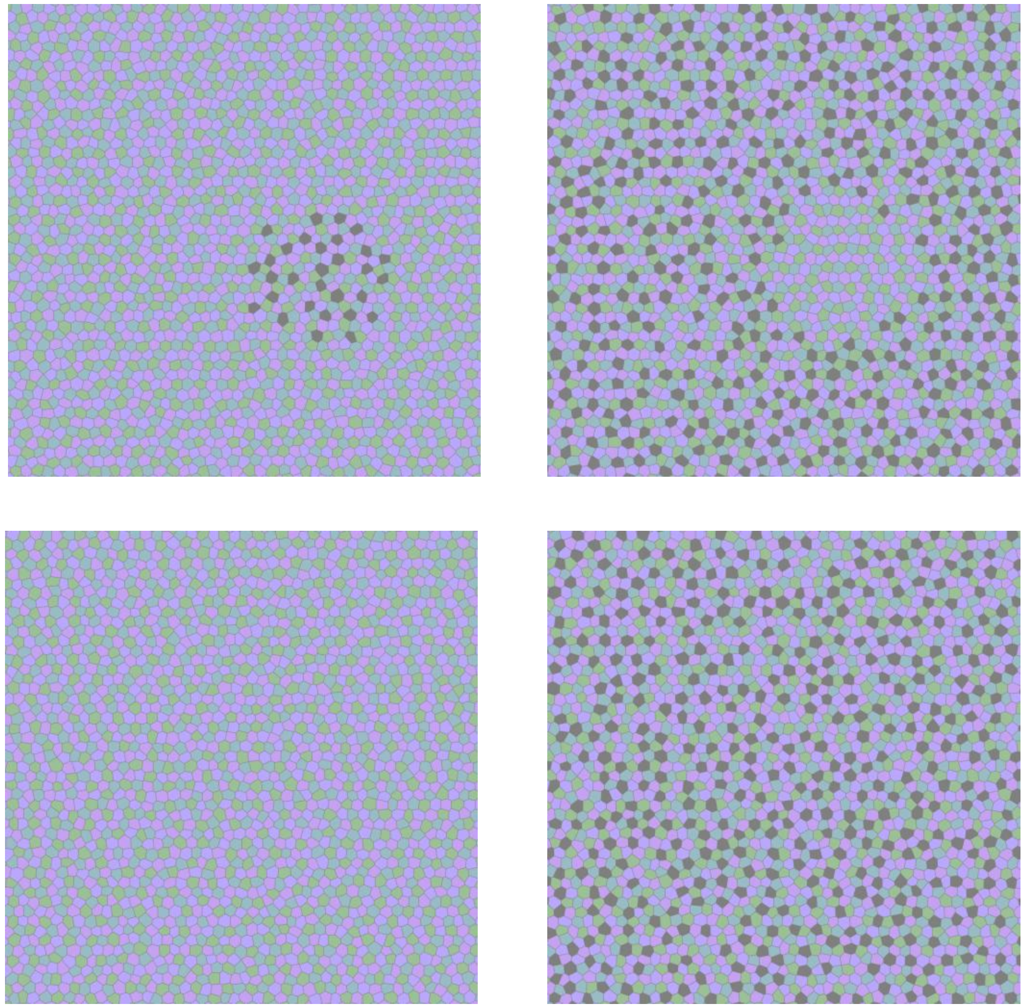


Figure 3. Illustration of the construction of patch and hole targets and corresponding catch trial stimuli against a four-colour background. The dark texture elements represent the fifth colour, for illustrative purposes only. The top left panel represent a patch stimulus where the fifth colour is added only in the target location. The top right panel represents a hole stimulus where the fifth colour is added everywhere except in the target location. The bottom panels represent the corresponding catch stimuli.

Teufel colours

The uniformly spaced isoluminant and iso-saturated hues used in the Voronoi textures were defined by Teufel and Wehrhahn (2000) and were specified in 1931 CIE space. Perceptual distances between these colours, as in other uniform colour spaces, are defined by hue angle around a colour circle. Distances from the centre of the circle are initially defined in cone contrast space as five just-noticable distances from the white point. This forms an ellipse in cone contrast space. Cone contrasts are then weighted to transform the ellipse to a circle, consistent with the model of Keuhni (2000). The resultant colours appear very similar in saturation. Further work defined 16 hue steps that are perceptually equal around the hue circle in the transformed cone space. For the present purposes, separable colours fall outside the angular range of a gamut of other colours, and non-separable colours fall within that angular range.

To accurately reproduce the colours on the CRT monitor, the procedure of Lucassen and Walraven (1990) was followed. First, the chromaticity coordinates of the monitor primaries were established (using the Minolta colorimeter) by making ten repeat measurements of the colour of a central block on the Sony monitor with the luminance level set at half the maximum output (128 out of 256). The block was half the area of the monitor, surrounded by its complementary colour in RGB space. Once the chromaticity of the primary colours was established, the output to luminance relationship was measured (gamma function). The chromaticities and gamma function were then used to determine the RGB values required to generate the set of Teufel colours using a linear transformation from 1931 CIE space to gamma-corrected RGB space.

Procedure

Before starting experimental trials, the visual search task was explained to participants. Participants were then given a set of practice trials to familiarise themselves with the target stimuli. Participants had the option to repeat practice trials if they needed more time to familiarise themselves with the targets. Participants were instructed to respond as quickly as possible while minimising errors, with particular emphasis on catch trials. Participants indicated target-present with a left click on a computer mouse and target-absent with a right click. In both the practice and experimental trials, participants were shown instructions and depressed spacebar to continue to the next stimulus display. If an incorrect response was entered, two types of feedback was provided. If participants responded ‘no’ on target-present trials (a miss), then a beep sounded. If participants responded ‘yes’ on catch trials (false positive), then a salient siren noise would sound followed by visual feedback with a count of the number of false alarms. In the experimental condition, there was only one experimental block that consisted of 192 target present trials, with different degrees of linear separability, as well as 96 catch trials that included no targets. Observers were excluded from further analysis if they made more than 20 false alarms (just over 20% of the total of 96 catch trials), on the basis that this represented an unacceptable rate of guessing.

Data Analysis

Participants' performance was measured by response times (RTs) and the proportion of errors. In addition to these standard measures, a validated integrated measure was utilized: the linear integrated speed-accuracy score (LISAS) (Vandierendonck, 2017; 2018). Conducting RT and error analysis separately, one might draw contradictory conclusions about an effect of a manipulation (Vandierendonck, 2017; 2018). Therefore, the purpose of using LISAS was to combine these two important performance aspects into a single measure of search difficulty. A high LISAS score, indicating difficult search, is obtained by having slow RTs and/or high proportion of errors. Alternatively, a low LISAS score, indicating easy search, is obtained by having fast RTs and/or low proportion of errors. Each participant's LISAS score was calculated for each condition using the following equation:

$$LISAS = RT_c + PE \times \frac{S_{RT}}{S_{PE}}$$

Where RT_C is the mean correct RT in each condition and *PE* is the participant's proportion of errors in each condition. S_{RT} and S_{PE} are the participant's overall RT and overall proportion of errors standard deviation *across all conditions* respectively. The use of these standard deviations means that the relative weight of RT and errors is optimised when comparing conditions.

Two statistical techniques were employed to compare the difficulty of search tasks using this combined measure. First, non-parametric bootstrapped pairwise comparisons were conducted between defined pairs of conditions using the method of Hall and Wilson (1991). The bias-corrected and accelerated bootstrap interval (BCa) was utilized to calculate confidence intervals because it is the most accurate and corrects for bias and skewness in the distribution of bootstrap estimates (Hall, 1988). Secondly, nonparametric Wilcoxon signed-rank tests were also used for repeated measure paired comparisons as a second method conducted to compare matched samples. This non-parametric test was also chosen due to the possibility of violating distributional assumptions.

Distributions of LISAS scores, response times and error rates were illustrated using standard boxplots (Tukey, 1977). In these plots, boxes represent the inter-quartile range, and a horizontal line in the middle of the box represents the median value. The “whiskers” on the plot represent the last value within 1.5 times the upper and lower interquartile ranges. Any values outside this range are plotted individually. Boxplots were used because the distributions departed markedly from normality.

Experiment 1

In the first experiment, we address the question of whether including a unique colour in the target, or removing of that unique colour, is optimal for minimising texture contrast and maximizing search difficulty. We tested this by investigating whether a search asymmetry could

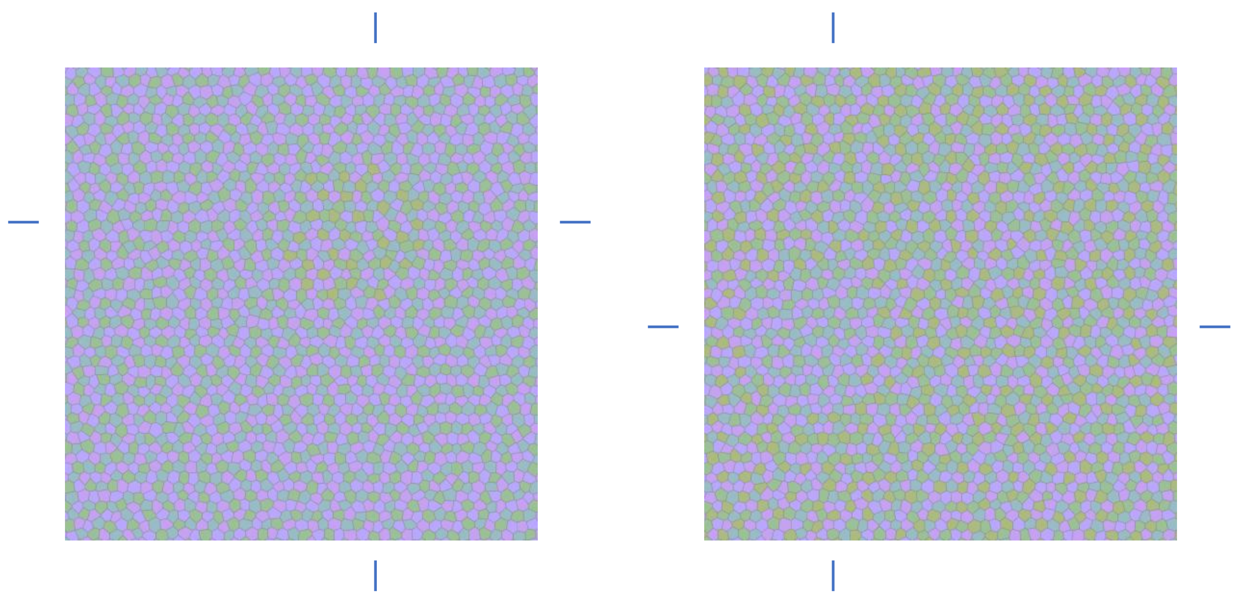


Figure 4. Example of Experiment 1 stimuli. Markers indicate the location of the targets in both diagrams. The left panel is an LS1 patch condition with a target defined by the presence of the fifth colour. The right panel is an LS1 hole condition with a target defined by the absence of the fifth colour. In both cases, the same Teufel colours were used

be observed between “patch” and “hole” targets. Furthermore, to contrast two competing accounts (Bauer et al. ,1996a, versus Vighneshvel and Arun, 2013), we examined how the linear separability of the missing or extra colour that defined the target affects search performance.

Methods

Twelve participants, aged 19-42 years (M = 22.92, SD = 6.42), took part in this study with apparatus, stimuli and procedure as described in General Methods. The experiment was a 2x4 factorial design, with both patch and hole stimuli that were either linearly non-separable (LNS) or linearly separable with a comparable inter-hue distance (LS1). We also included an additional linearly separable condition with a greater inter-hue distance (LS2; see Figure 5), and 4-coloured and 5-coloured catch trials (for patches and holes) respectively, yielding a total of 8 conditions. For all conditions, the Teufel colours in the Voronoi texture were counterbalanced by rotating around the gamut of Teufel colours to produce different sets of colours. (See Figures 4 and 5 for examples).

Results

Search difficulty as a function of target type (hole or patch) and linear separability is shown in Figure 6. Using LISAS as a measure of task difficulty, we observed a search asymmetry where search was more difficult for holes than for patches (for each of the three linear separability conditions). All planned comparisons between hole and patch targets were statistically significant (See Table 2), indicating a significantly greater difficulty finding hole targets in compared to patch targets. All comparisons survived correction for multiple comparisons using false discovery rate correction (Benjamini and Yuketieli, 2001) at the nominal rate of .05.

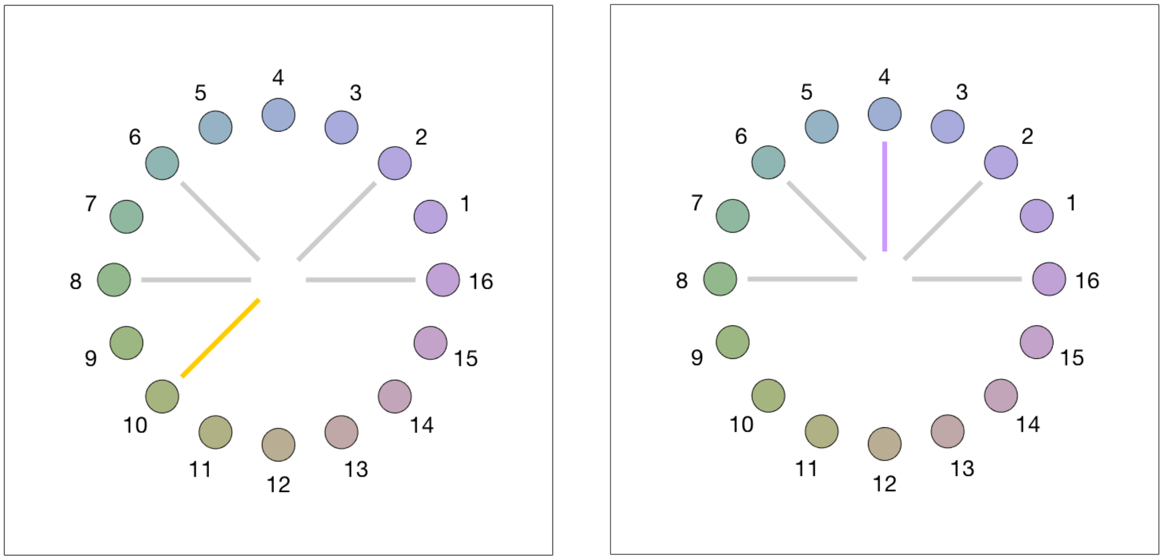


Figure 5. Gamut of Teufel colours with single example set of colours used in Experiment 1. Grey bars correspond to Teufel colours used both in the targets and in the background. The distance between any given neighbouring colours are two perceptually equidistant steps apart. In the left panel, the yellow bar corresponds to the fifth colour that defines either a patch or a hole. These five colours are reflected in both the LS1 example stimuli presented in Figure 4. This represents a linearly separable configuration where the fifth colour is linearly separable from the gamut of the other four Teufel colours. Note that the LS1 configuration can also be linearly separable with the fifth colour corresponding to Teufel colour 14. A configuration with a higher degree of linear separability (LS2) is also possible with the fifth colour corresponding to Teufel colour 12. (four steps apart) (Both not illustrated here). The right panel represents an LNS configuration where the fifth colour (purple bar) is positioned within the gamut of the other four Teufel colours and thus, linearly non-separable.

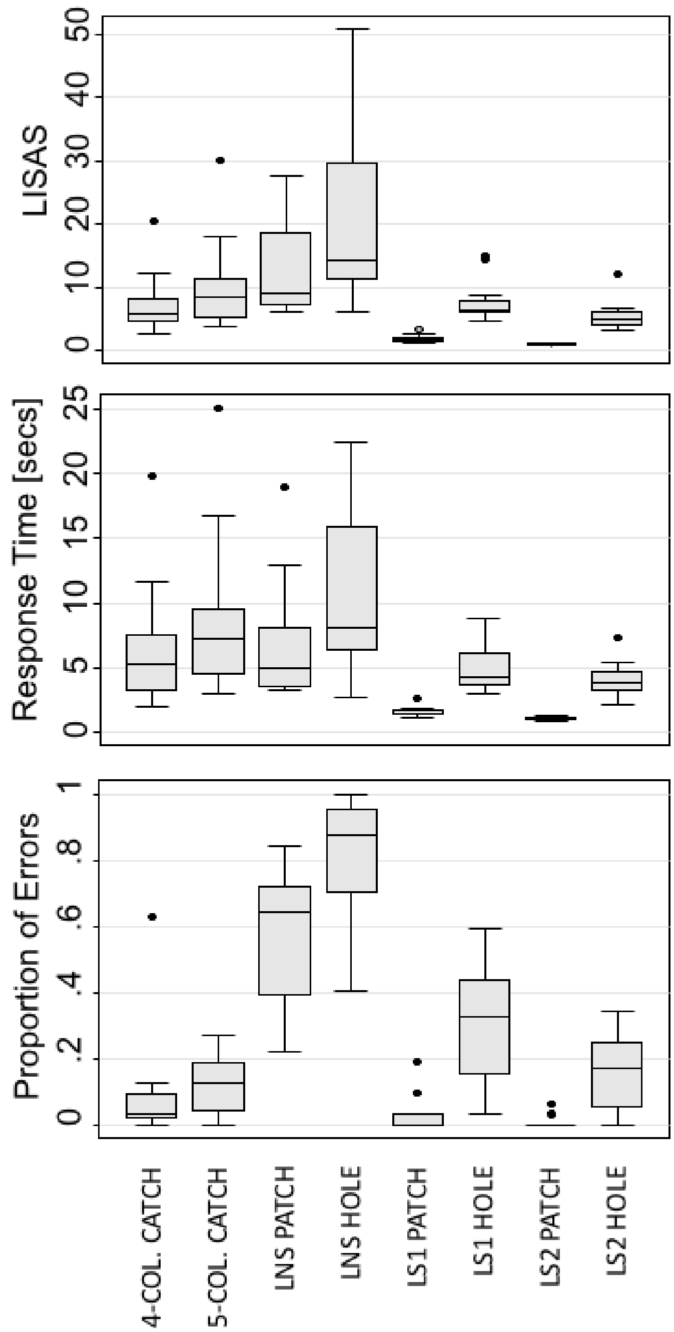


Figure 6. Boxplots of LISAS scores (top panel) response times (middle panel) and error rates (bottom panel) for the eight experimental conditions of Experiment 1.

Again using LISAS as a measure of task difficulty, we compared search difficulty across the three linear separability conditions (LNS, LS1, and LS2) examining patches and holes separately. All planned pairwise comparisons between these separability conditions were highly significant (See Table 1), and easily survived false discovery rate correction at the 5% level

(Benjamini and Yuketieli, 2001) showing that across both target types, search was more difficult in the linearly nonseparable condition (LNS) than in the other two conditions, and in turn search in the LS1 condition was more difficult than in the LS2 condition. In addition to these analyses using LISAS, in every case pairwise comparisons were also significant using at least one of RT or Error (see online supplementary material).

Table 1

Pairwise Comparisons for Linear Separability Conditions

LISAS Pairwise Comparison	Mean diff.	Bootstrap percentile *t*-test (one-tailed)		Bootstrap 95% confidence interval (BCa)		Wilcoxon rank test	
		t	*p*	Lower	Upper	Z	*p*
LNS patch vs. LS1 patch	11.07	5.18	<.0001	7.72	15.97	3.06	.002
LS1 patch vs. LS2 patch	0.85	5.16	<.0001	0.61	1.29	3.06	.002
LNS patch vs. LS2 patch	11.92	5.46	<.0001	8.52	16.99	3.06	.002
LNS hole vs. LS1 hole	12.90	3.49	.0001	7.24	21.49	2.98	.003
LS1 hole vs. LS2 hole	2.38	4.05	<.0001	.167	4.29	3.06	.002
LNS hole vs. LS2 hole	15.29	3.82	<.0001	9.44	25.08	3.06	.002

Planned pairwise comparisons using LISAS for patch and hole conditions (within separability conditions) are presented in Table 2. All comparisons were statistically significant and survived false discovery rate correction, indicating a greater difficulty in discriminating hole targets in comparison to patch targets for all separabilities. When considered in conjunction, LNS holes were the most difficult to find, followed by LNS patches.

Table 2

Pairwise Comparisons for Patch and Hole Conditions

LISAS Pairwise Comparison	Mean diff.	Bootstrap percentile *t*-test (one-tailed)		Bootstrap 95% confidence interval (BCa)		Wilcoxon rank test	
		t	*p*	Lower	Upper	Z	*p*
LNS patch vs. LNS hole	7.82	3.58	.0002	4.41	12.79	2.98	.003
LS1 patch vs. LS1 hole	5.99	6.67	<.0001	4.70	8.30	3.06	.002
LN2 patch vs. LS2 hole	4.45	6.54	<.0001	3.57	6.43	3.06	.002
4-coloured catch vs. 5-coloured catch	2.38	4.05	<.0001	1.68	4.29	2.98	.003

Discussion

The results of Experiment 1 confirm two of the three experimental hypotheses. In relation to linear separability, there is evidence to support the account presented by Bauer et al. (1996), because as the stimulus configuration goes from a high degree of linear separability to linear non-separability, search difficulty increases. This highlights the linear separability effect as a key determinant of search difficulty. In this particular paradigm, the results are not consistent with the predictions of Vighneshvel and Arun (2013). In both LNS and LS1 conditions, the fifth colour that defines a target is two perceptual steps apart from the nearest distractor colour. If search performance was determined by target-distractor dissimilarity/distance, there should be no difference between LNS and LS1 conditions. In relation to the search asymmetry, the findings provide evidence to support our hypothesis that search performance for hole conditions will be harder compared to patch conditions. In terms of camouflage design, this suggests that removing the unique colours from a camouflage pattern to be used against backgrounds that may not contain those colours is a better strategy when designing a compromise background matching camouflage.

Experiment 2

The previous experiment established (i) a robust effect of the linear separability of additional or missing texture colours and (ii) asymmetrical search times for holes and patches defined by the same texture colours. The findings suggested that removing unique additional colour(s) is optimum for concealment purposes. In this experiment, we return to the motivation for the present study, asking whether we can further improve on a universal camouflage pattern that would aim to be effective against multiple backgrounds. Experiment 2 investigated the effectiveness of hole targets against multiple different backgrounds. This was achieved by constructing two different backgrounds that shared four colours but differed in terms of a unique fifth colour (See Figure 7). Additionally, we sought to design a compromise between a patch and a hole target used in experiment 1 which we termed an "attenuated patch". The attenuated patch was composed of the four original colours common to both backgrounds, but additionally included two additional colours. These two additional colours were intermediate versions of *both* the unique colours present in the two backgrounds (i.e. the intermediate hue between the fifth colour in each background and the nearest of the four common background colours – see Figure 8). For any given attenuated patch, one of the two attenuated colours was linearly separable from the gamut of distractor colours. The other attenuated colour was located within the gamut of distractor colours and thus linearly non-separable.

Methods

Twelve participants, aged 19-25 years (M = 21.75, SD = 2.01), were recruited and viewed one block of 192 target-present trials and 96 catch trials. In this experiment, two differing backgrounds were constructed such that they shared four of the same colours, but a unique fifth colour defined each of the two backgrounds (colour gamuts are illustrated in Figure 7).

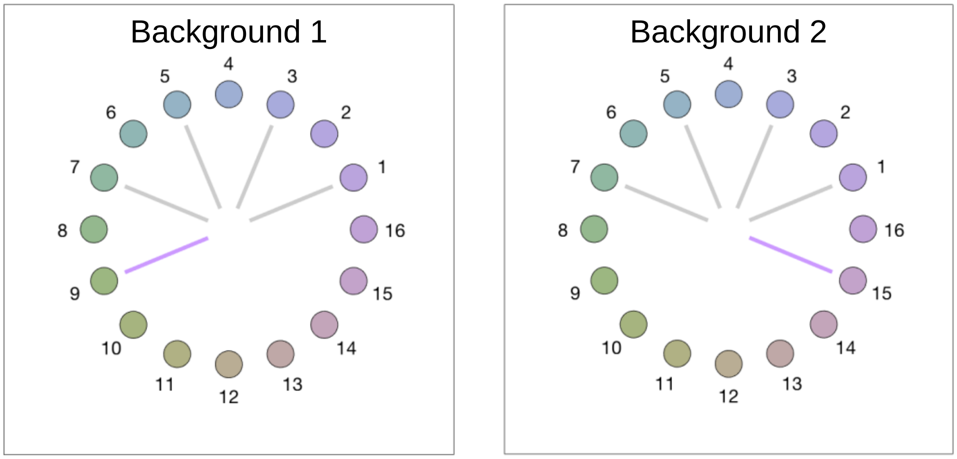


Figure 7. Gamut of Teufel colours indicating examples of two different backgrounds defined by a unique fifth colour. In both panels, both backgrounds share four common Teufel colours (grey bars). Purple bars indicate the unique Teufel colour that defines each background. In the left panel, background 1 is defined by Teufel colour 9. In the right panel, background 2 is defined by Teufel colour 15.

In three experimental conditions, the target was either a hole, a patch, or an attenuated patch. Each target was presented against two different backgrounds. The two different five-coloured backgrounds were also presented unaltered as catch trials. Catch trials, hole, and patch targets were constructed as described in General Methods. The attenuated patch was composed of the original four colours in both backgrounds and shared two 'attenuated' colours, each of which was only one perceptual step away from the gamut of the four consistent background colours. For any attenuated patch target, one of the attenuated colours was linearly separable, and one was linearly non-separable depending on the background (Figure 8). Similar to experiment 1, the Teufel colours in the Voronoi texture were counterbalanced around the hue circle.

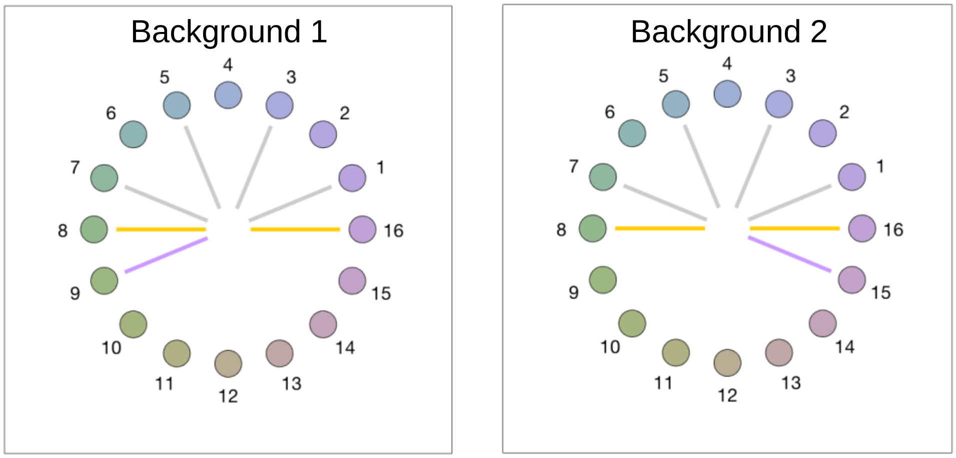


Figure 8. Gamut of Teufel colours demonstrating colours used in an attenuated patch against both backgrounds. In both backgrounds the attenuated patch contains four original Teufel colours utilized in both backgrounds (grey bars). The yellow bars indicate the two attenuated colours that are present in the attenuated patch. Purple bars correspond to the unique colour in either background. In background 1, colour 8 is linearly non-separable while colour 16 is linearly separable. The reverse is seen for background 2.

An attenuated patch was constructed similarly to targets in Experiment 1. Voronoi texture elements containing the fifth colour that defined either background 1 or 2 was overlaid onto the four-coloured base texture, but only *outside* the target position. This allowed the attenuated patch to not possess the unique fifth colour that defined either background. Next, the two attenuated colours that defined the attenuated patch were created each on separate textures, with the condition that single tiles have no identical adjacent colours. Only the tiles *within* the target position and radius of these second and third textures were then overlaid onto background 1 and 2 Voronoi textures to produce the attenuated patch targets. Examples of attenuated patch stimuli are presented below (Figure 9).

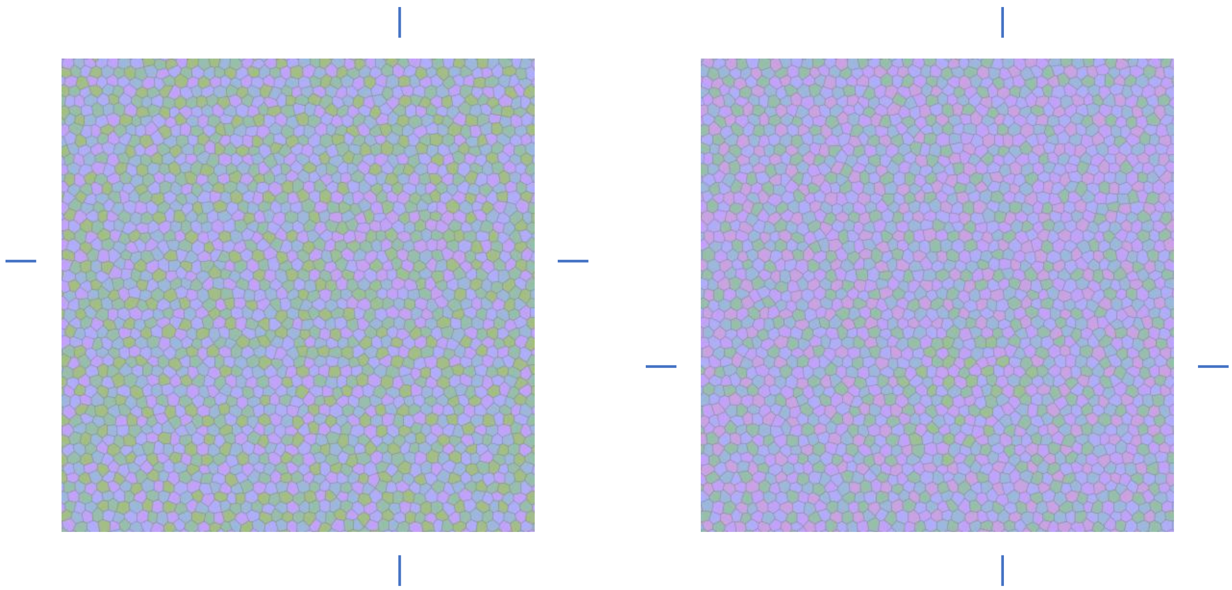


Figure 9. Example of attenuated patch stimuli. The left panel is an attenuated patch against background 1. The right panel is an attenuated patch against background 2. The attenuated patches set against both backgrounds are comprised of exactly the same Teufel colours. Markers at the edges of the panels indicate the position of the target patches, which were difficult to find without such cues.

Results

All planned pairwise comparisons using LISAS as a measure of task difficulty were statistically significant as shown in Table 3. In terms of search performance, holes were significantly more difficult to find than patches, and attenuated patches were significantly more difficult to find than patches. Most relevant to the present study, the critical comparison between hole and attenuated patch target types was significantly different, indicating a greater difficulty searching for attenuated patches compared to holes (Figure 10). When RT and proportion of errors were analysed separately, only the critical comparison between holes and attenuated patches using proportion of error was statistically significant (see online supplementary materials).

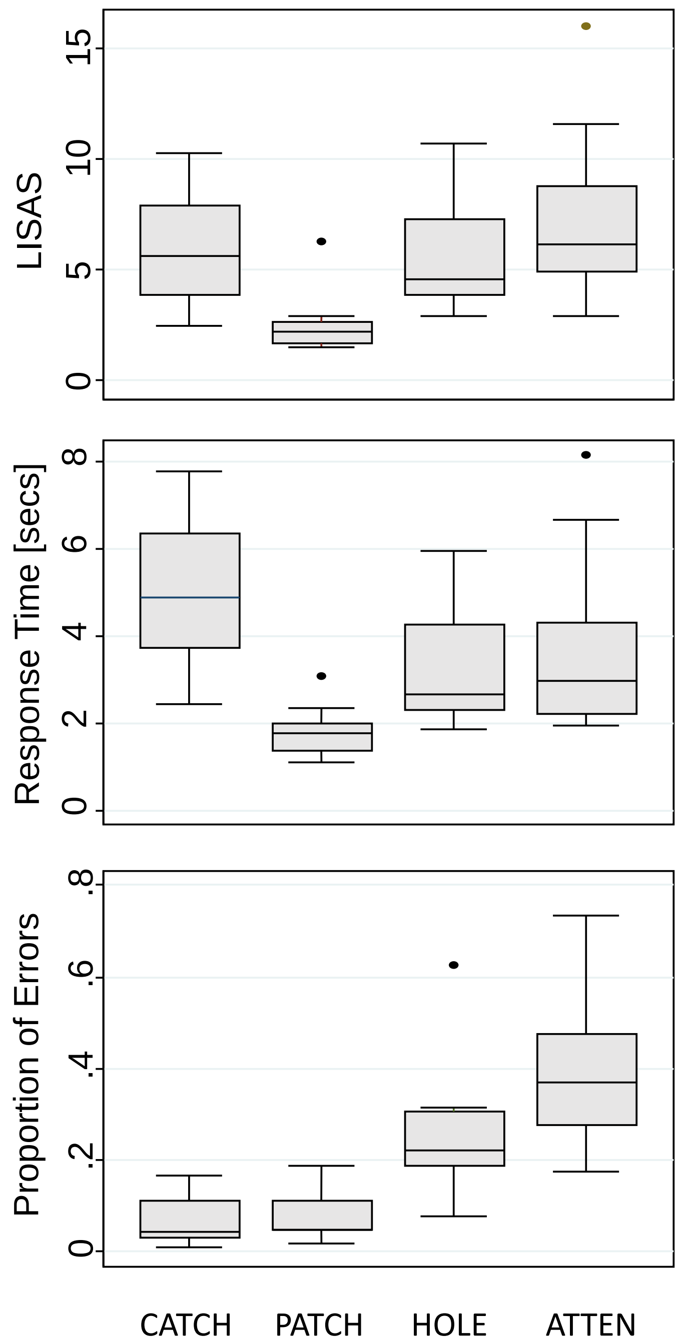


Figure 10. Results of Experiment 2. Boxplots of LISAS scores (top panel) response times (middle panel) and error rates (bottom panel) for catch trials, patch, hole, and attenuated patch (“atten”) conditions. On the combined LISAS measure, the critical comparison between attenuated patches and holes was significant. This was most apparent in terms of error rates.

Table 3

Pairwise Comparisons for Patch, Hole, and Attenuated Patch Conditions

LISAS Pairwise Comparison	Mean difference	Bootstrap percentile *t*-test (one-tailed)		Bootstrap 95% confidence interval (BCa)		Wilcoxon rank test	
		t	*p*	Lower	Upper	Z	*p*
Patch vs. Hole	3.08	5.49	<.0001	2.26	4.49	3.06	.002
Hole vs. Attenuated Patch	1.64	2.69	.0087	0.52	2.81	2.12	.034
Patch vs. Attenuated Patch	4.72	6.21	<.0001	3.46	6.39	3.06	.002

Discussion

In Experiment 2, we investigated whether hole targets were more difficult to find when presented against two different backgrounds. Furthermore, a compromise between a hole and a patch (which we named an *attenuated* patch) was designed to attempt to improve on the effectiveness of hole targets. Consistent with the findings from Experiment 1, holes were significantly more difficult to search for in comparison to patch targets using all three measures of task difficulty. Critically, using an integrated measure of search difficulty (LISAS) incorporating both accuracy and reaction time, the attenuated patch was significantly more difficult to find in comparison to hole targets. Using RT alone as a measure of task difficulty, the comparison did not reach significance (see online Supplementary materials). The results suggest that participants maintained a similar RT criterion when searching for holes and attenuated patch target types, and therefore the difference in search performance was primarily driven by the proportion of errors made in localizing the attenuated patch target.

Building on the findings of Experiment 1, which highlighted the potential effectiveness of hole targets for camouflage purposes, when a single background was extended to two different backgrounds as demonstrated in Experiment 2, an attenuated patch that contained intermediate versions of both the unique colours in both backgrounds was optimal for minimising texture contrast. In practical terms, the findings from Experiment 2 suggest that when designing a camouflage pattern for multiple terrains, a uniform containing colours that are attenuated versions of colours unique to particular backgrounds may be better than one that restricts the colour gamut to colours that are common to multiple backgrounds.

General Discussion

An important question when designing camouflage for use against multiple backgrounds is how best to handle the colours that uniquely identify the target (either by their presence or absence). Here, observers searched for texture patches on textured backgrounds, where targets were defined by either an extra colour or a missing colour in the patch. The results revealed a search asymmetry, whereby "hole" targets that lacked the presence of a unique fifth colour feature against a background that contained this fifth colour, were more difficult to find than "patch" targets that contained an additional colour relative to the background. An additional aim of this study was to test the competing theories by Vighneshvel and Arun (2013) and Bauer et al. (1996) regarding the effect of the linear separability of the colours in the textures on visual search efficiency, as applied to the case of multicoloured target and background textures. We observed that texture patches defined by the presence or absence of a fifth colour were harder to find when that colour fell within, rather than outside, the gamut of the other four colours. This was the case even when the perceptual distance to the most perceptually similar of the other four colours was held constant. This result corroborates Bauer et al.'s (1996) account and indicates that the linear separability of an additional or an absent texture colour is a key determinant of search difficulty.

Experiment 1 established that targets defined by an extra colour ("patches") are more visually conspicuous than the targets defined by an absent colour (“holes”). In Experiment 2, we considered the conspicuity of targets derived from, and set against, two different five-colour backgrounds. In this case, a target containing only the four common colours would represent a "hole" against both backgrounds, whereas a target containing all four colours common to both backgrounds, as well as the two colours unique to each background, would represent a "patch". Consistent with Experiment 1, we observed that the six-colour “patch” target was more conspicuous against both backgrounds than the four-colour “hole” target. We hypothesised that it might be possible to decrease the conspicuity of the “hole” target by adding *attenuated* colours: colours intermediate between the four common colours and the two unique colours. We observed that attenuated six-colour targets were indeed more difficult to find than pure "hole" targets. In other words, insofar as the difference between the additional colours and the backgrounds increased the conspicuity of the target, this was more than compensated for by the reduction in conspicuity resulting from the elimination of the missing colours. This has important practical implications for camouflage design: a camouflage pattern that is intended to be effective against multiple backgrounds might be optimised by including the shared colour palette but adding attenuated versions of the colours unique to the different backgrounds.

It is important to acknowledge that in the case of linear separability effects relating to multicoloured textures, the situation is more complex than in the case of single-coloured targets among single-coloured (but heterogenous) distractors. Bauer et al. (1998) proposed the additive colour mixture hypothesis as a possible explanation of linear separability effects in the latter situation. This hypothesis states that saliency effects should not be present when a target falls between distractors because the target is equivalent to the average of the distractor chromaticities (e.g. an orange target amongst red and yellow distractors). This hypothesis is directly applicable to those conditions where linearly non-separable target patches are defined by colours that fall in the middle of the gamut of distractor colours, and therefore correspond to the average of distractor chromaticities. On the other hand, targets defined by linearly separable colours shift the average colour of a patch away from the average colour of the background. With relatively dense continuous textures, this hypothesis becomes more relevant, and may partly explain the linear separability effects observed in this study.

The additive colour mixture hypothesis cannot provide a full explanation of the present findings, because it does not explain the observed asymmetry between "patch" and "hole" targets. When the target and background textures are exchanged, the average colour difference remains constant, but search is much more difficult for "hole" targets. It is therefore necessary to appeal to the hypotheses set out earlier to explain this asymmetry. The finding is consistent with both of those hypotheses. According to Treisman and Souther (1985), the absence of a feature is harder to detect than the presence of an additional feature. A "hole" target is a region of texture that lacks a colour relative to the background. The background also contains an additional colour relative to the target, so the background may be considered to be visually noisier than the target, consistent with the theory of Vincent (2011).

An incidental finding that is relevant to this question is provided by the results of the catch trials. In the first experiment, four-coloured catch trials were significantly more efficient (across all three difficulty measures) than five-coloured catch trials. Since the Voronoi texture spanned the entire visual display, and the presence or absence of the target was defined by a single colour, it is possible that the observers attended to one colour at a time when looking for a “patch or hole”. Evidence for spatially global feature-based selection has emerged from the study of speeded judgements of the asymmetry of four-coloured textures. Morales and Pashler (1999) obtained speeded judgements of the asymmetry of 4x8 grids comprised of squares of four different colours. In the asymmetric grids, 4 squares did not display mirror asymmetry across the vertical midline. However, when the asymmetry involved all four colours rather than just two of the colours, response times were faster. Morales and Pashler (1999) concluded that their observers were judging the symmetry of the displays one colour at a time. Stuart, Barsdell and Day (2014) showed that hue, lightness and saturation could independently contribute to this task (as the original study confounded lightness with hue and saturation). The finding that the absence of a target in the four colour textures could be determined faster than the absence of a target in a five-colour texture is consistent with the hypothesis of simultaneous feature-based selection of multiple elements, colour by colour, within complex arrays.

A body of research that is relevant to the present question comes from attempts to build models of visual saliency. According to saliency models such as that of Itti, Koch and Neibur (1998) and its successors, individual feature contrasts, such as those identified in visual search paradigms, are combined additively into a single spatial representation of overall conspicuity. Locations in the visual field then compete for attention, which is then directed to the most salient location. Texture contrast is part of some saliency models (Zhang, Yang and Luo, 2016), but the preferential looking paradigm is best suited to distinguishing between the salience of objects or regions of relatively high conspicuity. It is therefore less suited to the study of low levels of conspicuity relevant to camouflage. Nonetheless, studies of visual conspicuity using visual search and rapid texture discrimination paradigms could be used to inform the development of more comprehensive saliency models.

It is important to note that there are fundamental limits to the effectiveness of a compromise camouflage. In the present study, the presence or absence of more linearly separable colours (four steps on the Teufel hue circle) was enough to make the targets easily detectible. The use of attenuated colours reduced search efficiency against different backgrounds. Under more realistic search conditions, including wider fields of view and more naturalistic environments, the range of effectiveness might be extended to tolerate even more separable colours before camouflage effectiveness breaks down. However, if visual environments are too distinctive, an effective compromise camouflage may not be possible. This may explain the observation of Hughes et al. (2019) that compromise camouflage does not appear to be a common strategy in the animal world. It may also explain why the attempt to design a universal military camouflage pattern (Dugas et al., 2004) was ill-fated.

In the natural camouflage literature, it has been argued that "distractive markings" can both assist (e.g., Dimitrova, Stobb, Shaefer and Merailta, 2009) and reduce camouflage (Stevens et al., 2012). From the perspective of background matching, the addition of a very distinctive colour sufficient to cause distraction of attention away from the form of a target would reduce camouflage effectiveness. In natural environments there may be a trade-off sufficient to produce an overall benefit of distractive markings, where those markings may be more salient than the outline form of the animal. However, in the textures used in this experiment there are weak boundary cues (if any). Detection in this study was therefore based on contrast between target and background surfaces, and the more separable colours aided target detection. Our findings therefore apply only to the issue of background matching camouflage, not other types of camouflage.

There are some limitations of the present study that could be addressed by further research. For simplicity, when adding or subtracting colours from textures, we did not shift the hues of the other colours to maintain the same average hue. Doing this might be a way to further optimise camouflage effectiveness. In more applied experiments informed by the present research, it would be interesting to use colour palettes from natural environments, and to consider the effect of different numbers of colours comprising the textures. It would also be important to investigate other aspects of visual contrast, such as lightness and saturation. It would also be informative to look at how the size, shape and distribution of texture elements might affect the conspicuity of texture patches designed for use against more than one background. It is possible the same principles that apply to the choice of hues would also apply to the choice of texture elements when designing a “hybrid” texture. For example, linear separability and asymmetry effects might apply to the size or shape of individual texture elements.

References

Akl, A., Yaacoub, C., Donias, M., Da Costa, J-P. & Germain, C. (2018). A survey of examplar-based texture synthesis algorithms. *Computer Vision and I mage Understanding, 172,* 12-24.

Anonymous (2009). *Photosimulation Camouflage Detection Test.* NATICK/TR-09-021L. Natick, MA: U.S. Army Natick Soldier Research, Development and Engineering Center.

Balas, B.J. (2006). Texture synthesis and perception: Using computational models to study texture representations in the human visual system. *Vision Research, 46,* 299-309.

Bauer, B., Jolicoeur, P., & Cowan, W. B. (1996a). Visual search for colour targets that are or are not linearly separable from distractors. *Vision Research, 36*(10), 1439-1465.

Bauer, B., Jolicoeur, P., & Cowan, W. B. (1998). The linear separability effect in colour visual search: ruling out the additive colour hypothesis. *Perception & Psychophysics, 60*(6), 1083-1093.

Benjamini, Y. & Yekutieli, D. (2001). The control of the false discovery rate in multiple testing under dependency. *Annals of Statistics, 29*(4), 1165-1188.

Brainard, D.H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433-436.

Bruce, N.D.B., Wloka, C., Frosst, N. & Tsotsos, J.K. (2015). On computational modelling of visual saliency: Examining what's right and what's left. *Vision Research, 116 (Part B),* 95-112.

Cott, H.B. (1940). *Adaptive Coloration in Animals*. London: Methuen & Co. Ltd.

Cuthill, I.C. (2019). Camouflage. *Journal of Zoology, 308*(2), 75-92.

Dimitrova, M., Stobbe, N., Schaefer, H.M. & Merilaita, S. (2009). Concealed by conspicuousness: distractive prey markings and backgrounds. *Proceedings of the Royal Society B: Biological Sciences, 276,* 1905-1910.

D'Zmura, M. (1991). Colour in visual search. *Vision Research, 31*(6), 951-966.

Dugas, A., Zupkofska, K. J., DiChiara, A. & Kramer, F. M. (2004). *Universal Camouflage for the Future Warrior*. DTIC-ADA433081. Natick, MA: U.S. Army Research, Development and Engineering Command, Natick Soldier Center.

Freeman J., Ziemba C.M., Heeger D.J., Simoncelli E.P. & Movshon J.A. (2013) A functional and perceptual signature of the second visual area in primates. *Nature Neuroscience, 16*(7), 974–981.

Hall, P. (1988). Theoretical comparison of bootstrap confidence intervals. *The Annuals of Statistics, 16*(3), 927-953.

Hall, P., & Wilson, S.R. (1991). Two guidelines for bootstrap hypothesis testing. *Biometrics,* 47(2), 757-762.

Hughes, A., Liggins, E. & Stevens, M. (2019). Imperfect camouflage: how to hide in a variable world? *Proceedings of the Royal Society B, 286*, 20190646.

Itti, L., Koch, C. & Neibur, E. (1998). A model of saliency-based attention for rapid scene analysis. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 20*(11), 1254-1259.

Julesz, B. (1981). Textons, the elements of texture perception, and their interactions. *Nature, 290,* 91-97.

Kuehni, R.G. (1998). Hue uniformity and the CIELAB space and color difference formula. *Color Research & Application, 23,* 314–322.

Kuehni, R.G. (2000). Uniform color space modeled with cone responses. *Color Research & Application, 25*(1), 56-63.

Lindsey, D. T., Brown, A. M., Reijnen, E., Rich, A. N., Kuzmova, Y. I., & Wolfe, J. M. (2010). Colour channels, not colour appearance or colour categories, guide visual search for desaturated colour targets. *Psychological Science, 21*(9), 1208-1214.

Lucassen, M., & Walraven, J. (1990). Evaluation of a simple method for color monitor recalibration. *Color Research and Application, 15*(6), 321-326.

Melgosa, M., Quesada, J.J. & Hita E. (1994). Uniformity of some recent color metrics tested with an accurate color-difference tolerance dataset. *Applied Optics, 33*(34), 8069-8077.

Merilaita, S., Lyttinen, A. & Mappes, J. (2001). Selection for cryptic coloration in a visually heterogeneous habitat. *Proceedings of the Royal Society of London B, 268,* 1925-1929.

Morales, D., & Pashler, H. (1999). No role for colour in symmetry perception. *Nature, 399,* 115-116.

Morillas, S. & Fairchild, M.D. (2018). Using suprathreshold color-difference ellipses to estimate any perceptual color-difference. *Journal of Visual Communication and Image Representation, 55,* 142-148.

Parkhurst, D.J & Neibur, E (2004). Texture contrast attracts overt visual attention in natural scenes. *The European Journal of Neuroscience, 19,* 983-9.

Portilla J. & Simoncelli, E.P. (2000). A parametric texture model based on joint statistics of complex wavelet coefficients. *International Journal of Computer Vision, 40(1),* 49–71.

Potechin, C. & Gursey, R. (2006). Texture discrimination asymmetries across the visual field. *Spatial Vision, 19*(5), 389–412.

Rosenholtz, R. (2001). Search asymmetries? What search asymmetries? *Perception & Psychophysics, 63*(3), 476-489.

Rubenstein, B.S & Sagi, D. (1990). Spatial variability as a limiting factor in texture-discrimination tasks: Implications for performance asymmetries. *Journal of the Optical Society of America A, 7,* 1632-1643.

Schaefer, H.M. & Stobbe, N. (2006). Disruptive coloration provides camouflage independent of background matching. *Proceedings of the Royal Society, Series B, 273,* 2427–2432.

Stevens, S., Cuthill, I.C., Windsor, A.M.M. & Walker H.J. (2006). Disruptive contrast in animal camouflage. *Proceedings of the Royal Society, Series B, 273,* 2433–2438.

Stevens, M., Marshall, K.A., Troscianko, J., Finlay, S., Burnand, D. & Chadwick, S.L. (2012). Revealed by conspicuousness: distractive markings reduce camouflage. *Behavioral Ecology, 24*(1),213-222.

Stuart, G. W., Barsdell, W. N., & Day, R. H. (2014). The role of lightness, hue and saturation in feature-based visual attention. *Vision Research, 96,* 25-32.

Terzic, K., Krishna, S., & du Buf, J. M. H. (2017). Texture features for object salience. *Image and Vision Computing, 67,* 43-51.

Teufel, H. J., & Wehrhahn, C. (2000). Evidence for the contribution of S cones to the detection of flicker brightness and red-green. *Journal of the Optical Society of America, 17*(6), 994-1006.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review, 95,* 15-48.

Treisman, A., & Souther, J. (1985). Search asymmetry: a diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General, 114*(3), 285-310.

Troscianko J., Skelhorn J. & Stevens M. (2018) Camouflage strategies interfere differently with observer search images. *Proceedings of the Royal Society, Series B, 285*, 20181386.

Tukey, J.W. (1977). *Exploratory Data Analysis.* Reading, MA: Addison-Wesley.

Vandierendonck, A. (2017). A comparison of methods to combine speed and accuracy measures of performance: A rejoinder on the binning procedure. *Behavior Research Methods, 49*(2), 653-673.

Vandierendonck, A. (2018). Further tests of the utility of integrated speed–accuracy measures in task switching. *Journal of Cognition, 1,* 8.

Victor, J.D., Conte, M.M. & Chubb, C.F. (2017). Textures as probes of visual processing. *Annual Review of Vision Science, 3,* 275–96.

Vighneshvel, T., & Arun, S. P. (2013). Does linear separability really matter? Complex visual search is explained by simple search. *Journal of Vision, 13*(11), 1-24.

Vincent, B.T. (2011). Search asymmetries: Parallel processing of uncertain sensory information. *Vision Research, 51,* 1741-1750.

Wolfe, J. M. (2001). Asymmetries in visual search: an introduction. *Perception & Psychophysics, 63*(3), 381-389.

Zhang, L., Yang, L. and Luo, T. (2016). Unified saliency model using colour and texture features. *PLoS One, 11*(2), e0149328.

Acknowledgements

HH was supported by the Australian Government through the Australian Research Council's Discovery Projects funding scheme (project DP180102268).

Online Supplementary Material

Appendix 1

Bootstrapped Pairwise Comparisons and Wilcoxon Signed-Rank Test using RT Measure for Experiment 1

RT Pairwise Comparison (secs)	Mean diff.	Bootstrap percentile *t*-test (one-tailed)		Bootstrap 95% confidence interval (BCa)		Wilcoxon rank test	
		t	*p*	Lower	Upper	Z	*p*
4-colour catch vs. 5-colour catch	2.23	5.13	<.0001	1.62	3.35	3.06	.002
LNS patch vs. LNS hole	4.01	3.86	<.0001	2.53	6.67	2.90	.004
LS1 patch vs. LS1 hole	3.28	6.50	<.0001	2.45	4.37	3.06	.002
LS2 patch vs. LS2 hole	3.02	8.04	<.0001	2.45	3.92	3.06	.002
LNS patch vs. LS1 patch	5.18	3.77	<.0001	3.24	9.03	3.06	.002
LS1 patch vs. LS2 patch	0.62	6.23	<.0001	0.48	0.90	3.06	.002
LNS patch vs. LS2 patch	5.80	4.18	<.0001	3.91	9.68	3.06	.002
LNS hole vs. LS1 hole	5.91	3.33	.0005	3.10	9.80	2.82	.005
LS1 hole vs. LS2 hole	0.87	2.38	.010	0.29	1.70	1.80	.071
LNS hole vs. LS2 hole	6.79	3.88	.0001	4.07	10.90	3.06	.002

Appendix 2

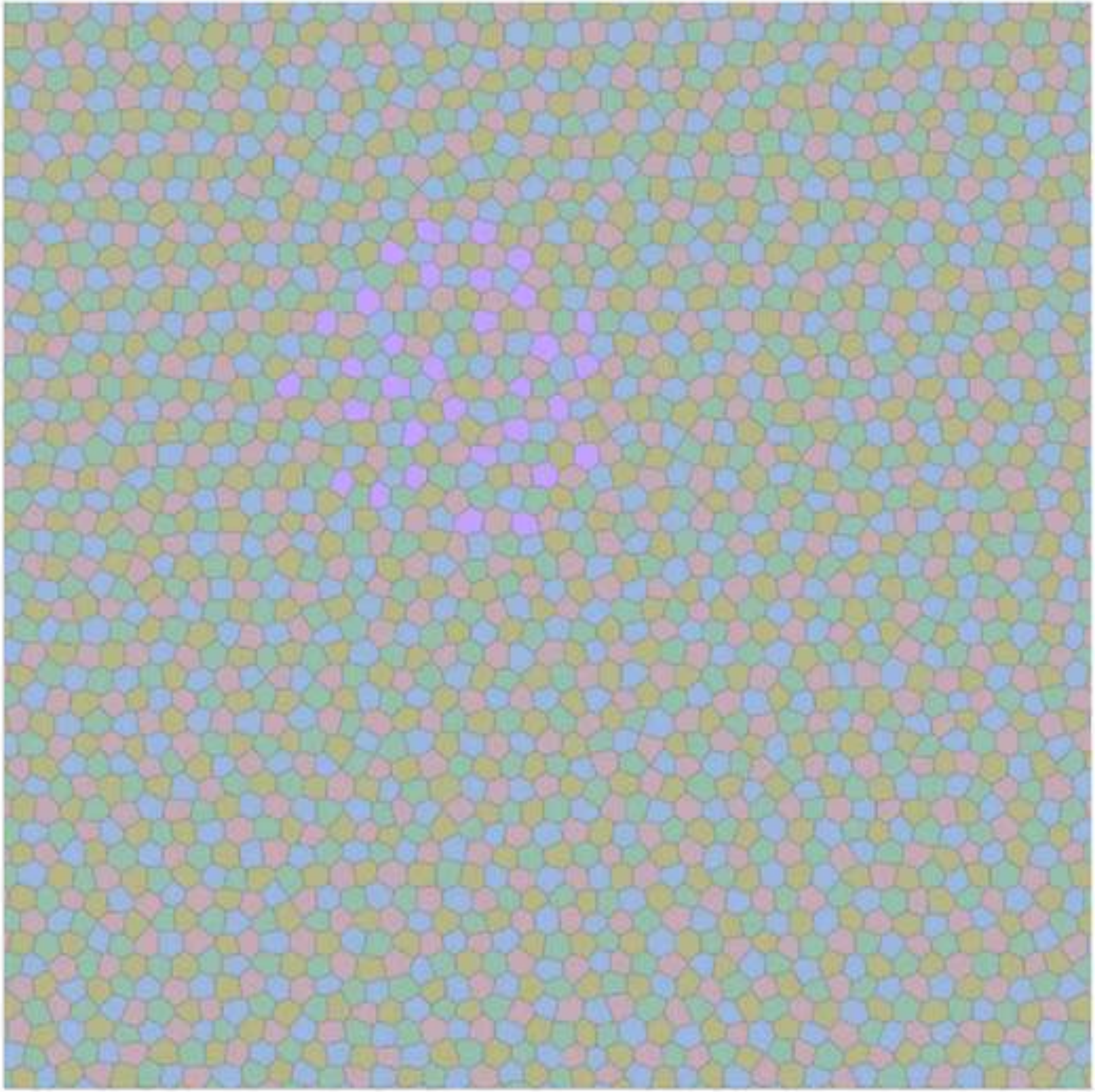
Bootstrapped Pairwise Comparisons and Wilcoxon Signed-Rank Test using Proportion of Error Measure for Experiment 1

Proportion of Errors Pairwise Comparison	Mean diff.	Bootstrap percentile *t*-test (one-tailed)		Bootstrap 95% confidence interval (BCa)		Wilcoxon rank test	
		t	*p*	Lower	Upper	Z	*p*
4-colour catch vs. 5-colour catch	0.32	7.86	<.0001	0.25	0.41	3.03	.002
LNS patch vs. LNS hole	0.22	5.06	<.0001	0.14	0.31	3.03	.002
LS1 patch vs. LS1 hole	0.28	5.72	<.0001	0.20	0.39	3.06	.002
LS2 patch vs. LS2 hole	0.16	4.93	<.0001	0.10	0.22	3.03	.003
LNS patch vs. LS1 patch	0.55	11.17	<.0001	0.45	0.63	3.07	.002
LS1 patch vs. LS2 patch	0.02	1.56	.275	0.003	0.07	1.33	.184
LNS patch vs. LS2 patch	0.58	10.67	<.0001	0.46	0.66	3.06	.002
LNS hole vs. LS1 hole	0.49	9.64	<.0001	0.36	0.56	3.06	.002
LS1 hole vs. LS2 hole	0.15	3.40	.006	0.08	0.26	2.67	.008
LNS hole vs. LS2 hole	0.64	11.51	<.0001	0.53	0.74	3.06	.002

Appendix 3

Bootstrapped Pairwise Comparisons and Wilcoxon Signed-Rank Test using RT and Proportion of Error Measures for Experiment 2

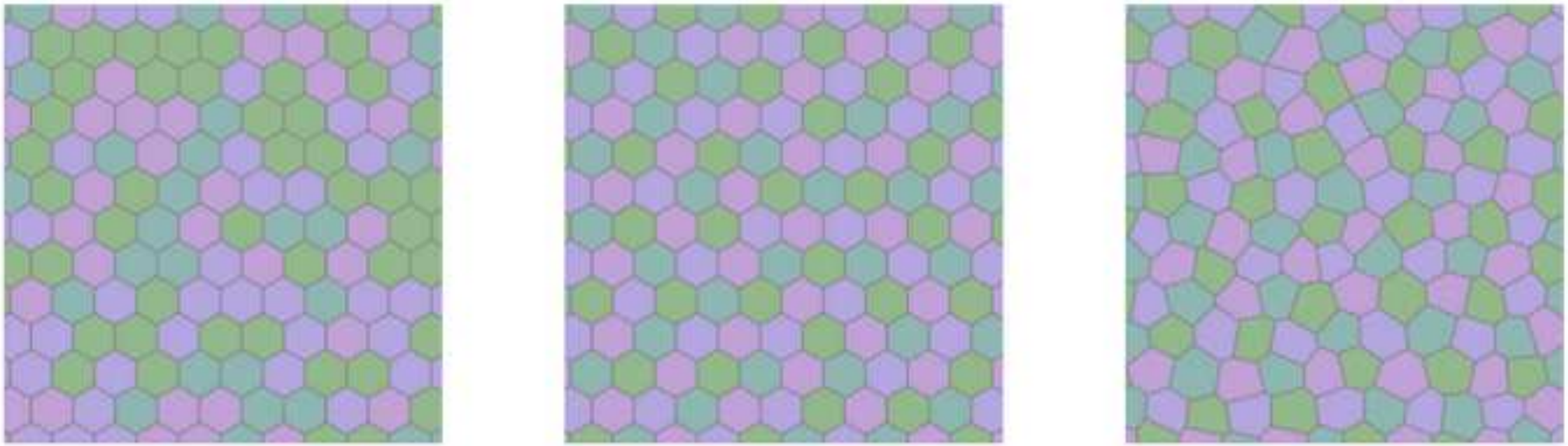
Pairwise Comparison	Mean diff.	Bootstrap percentile *t*-test (one-tailed)		Bootstrap 95% confidence interval (BCa)		Wilcoxon rank test	
		t	*p*	Lower	Upper	Z	*p*
RT (secs)							
Patch vs. Hole	1.46	5.04	<.0001	1.02	2.15	3.06	.002
Hole vs. Attenuated Patch	0.42	1.40	.059	-0.03	1.15	1.49	.136
Patch vs. Attenuated Patch	1.87	4.41	.0001	1.25	2.92	3.06	.002
Proportion of Error							
Patch vs. Hole	0.18	5.76	<.0001	0.13	0.25	3.07	.002
Hole vs. Attenuated Patch	0.14	4.43	.0004	0.08	0.19	2.82	.005
Patch vs. Attenuated Patch	0.32	7.86	<.0001	0.25	0.41	3.06	.002



Background

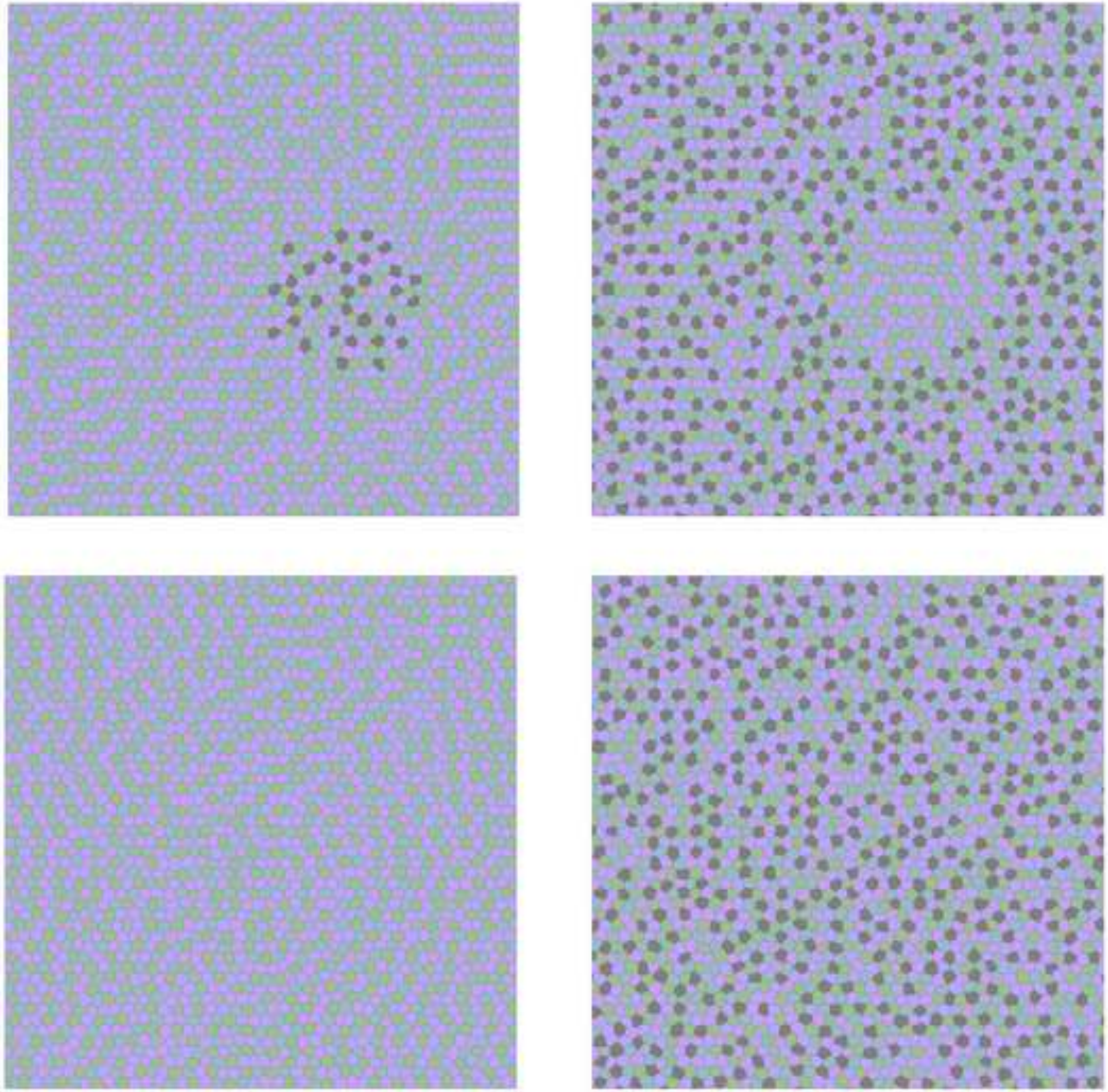
Figure

Click here to download high resolution image



Slide02.tiff

Figure
Click here to download high resolution image



Slide03.tiff

Slide04.tiff

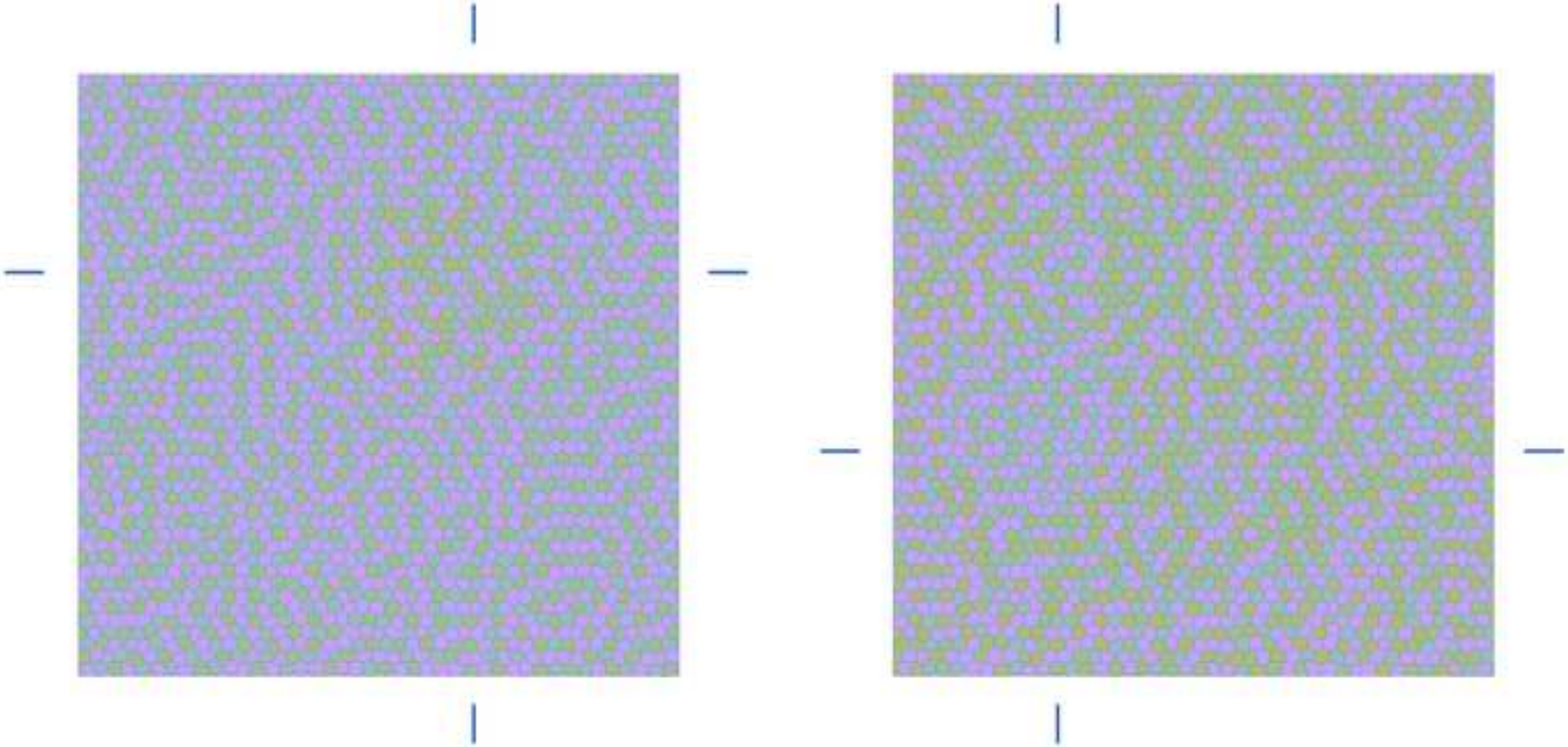
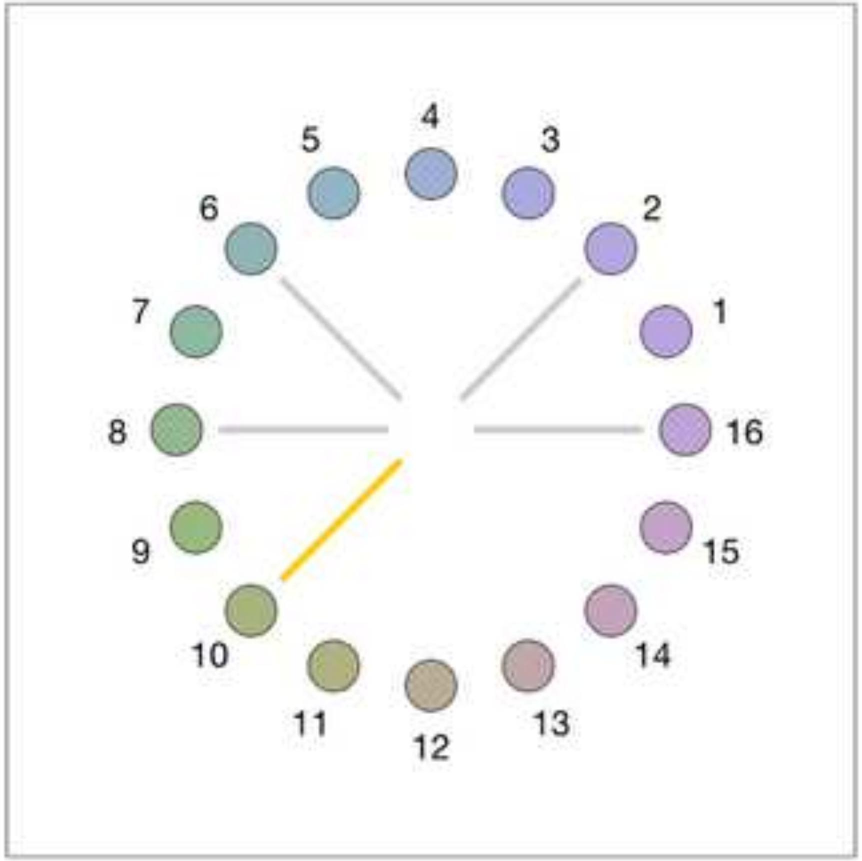
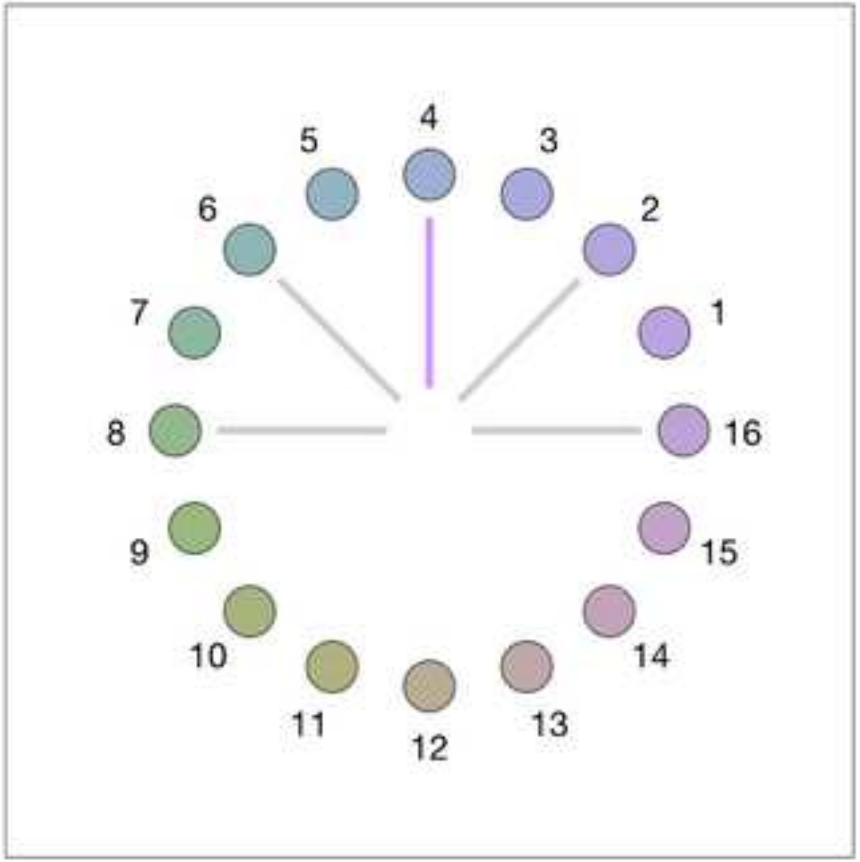


Figure
Click here to download high resolution image





Slide05.tiff

Figure
Click here to download high resolution image

Slide06.tiff

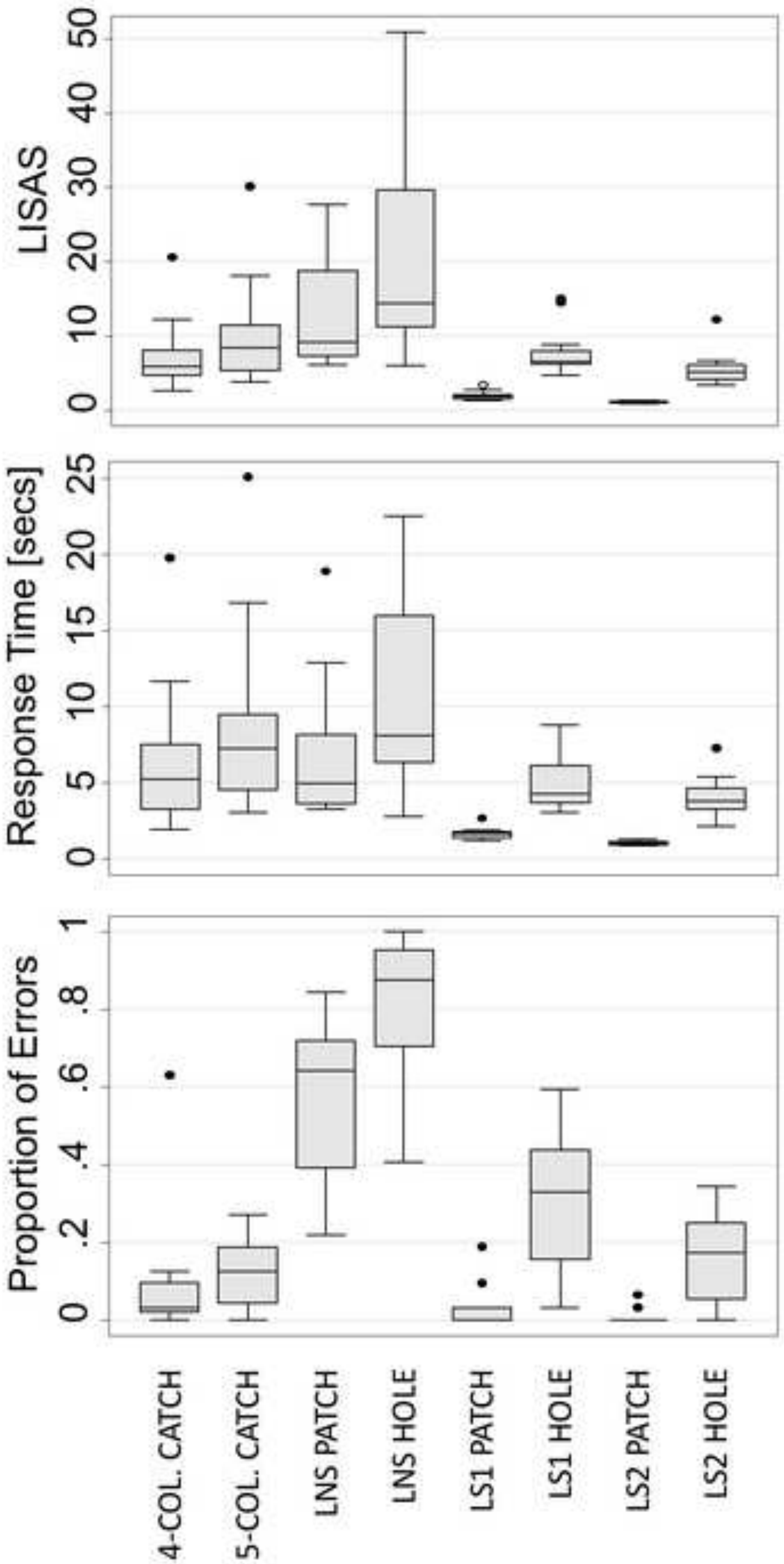
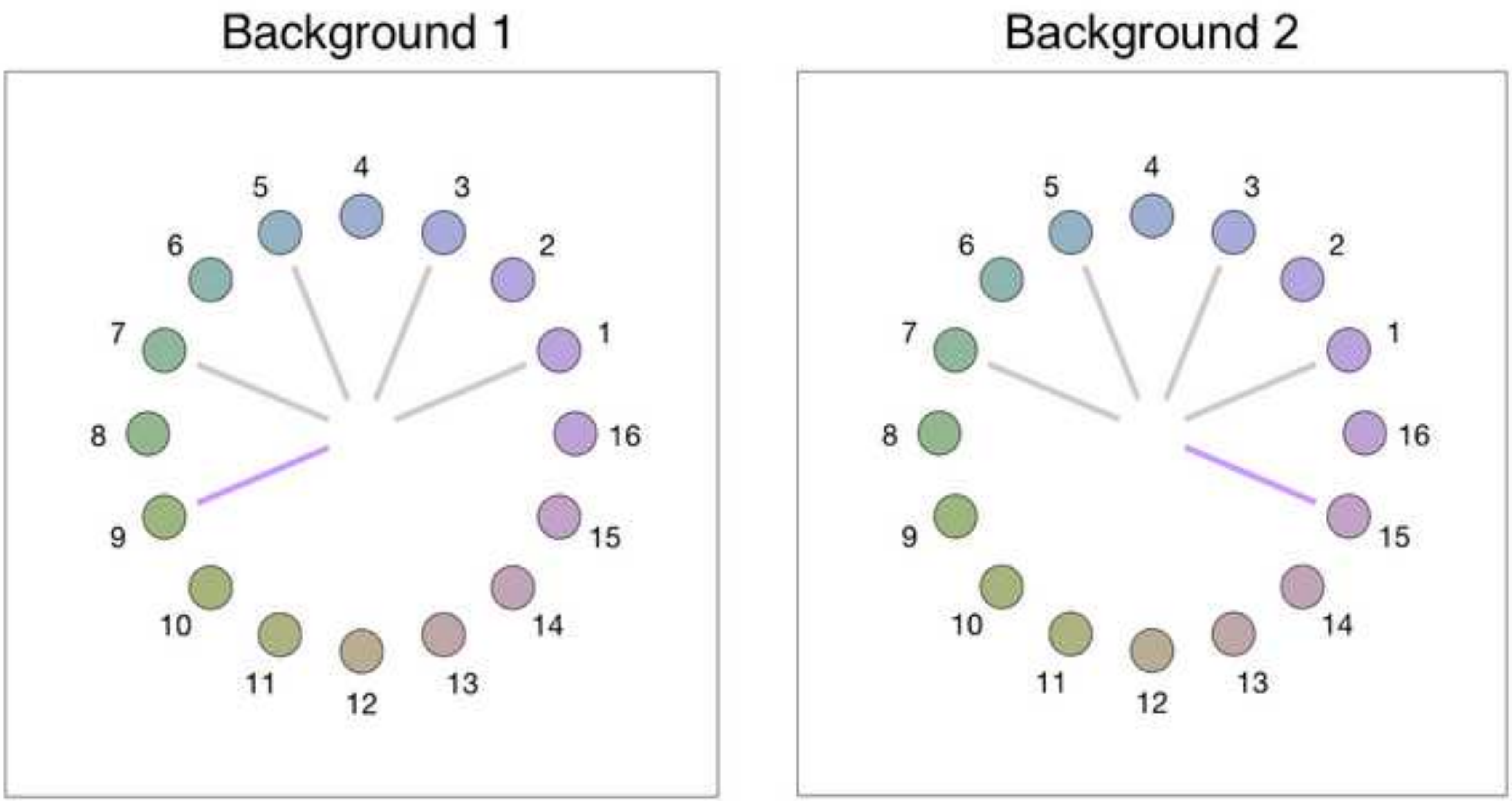
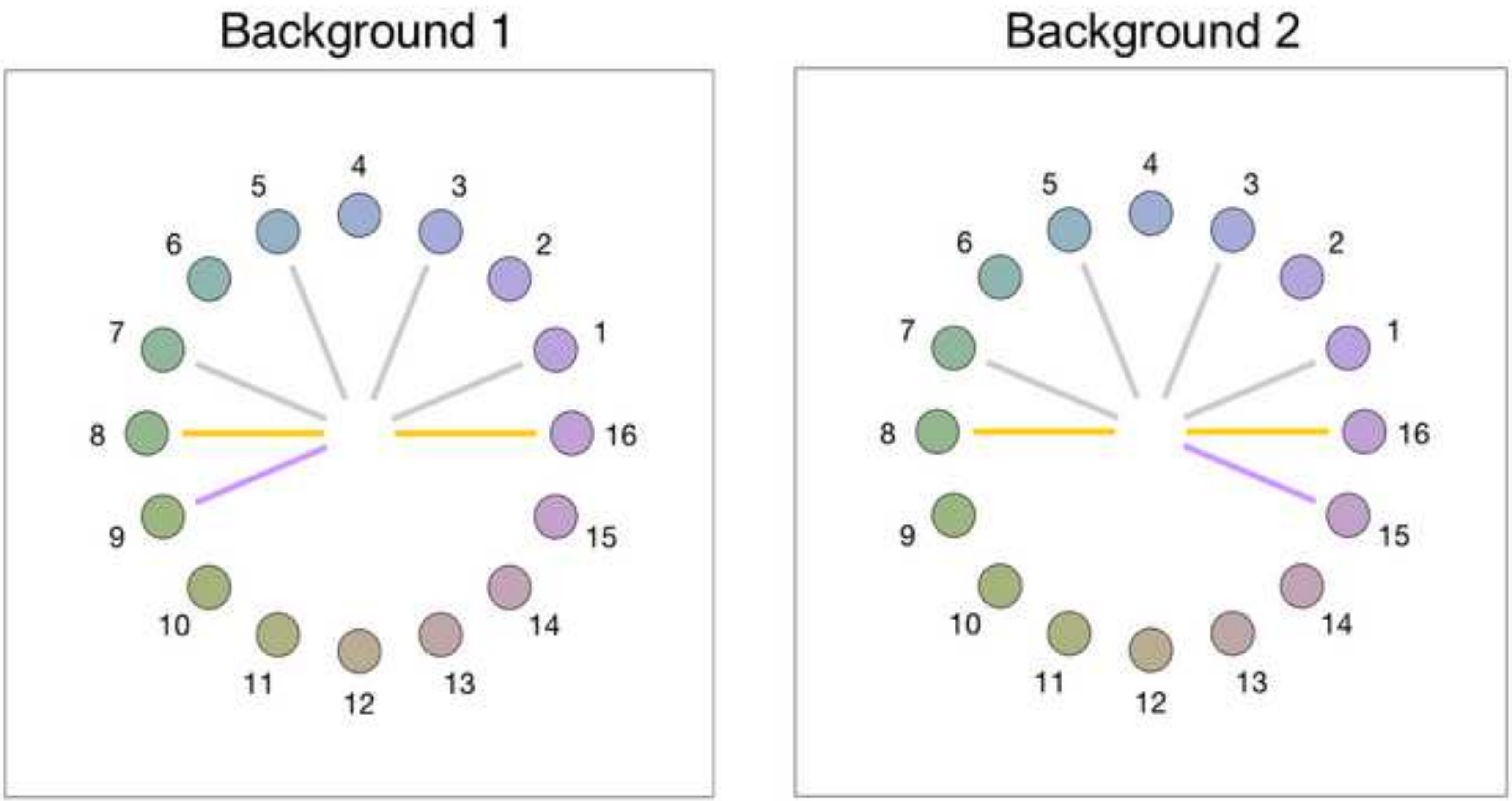


Figure
Click here to download high resolution image



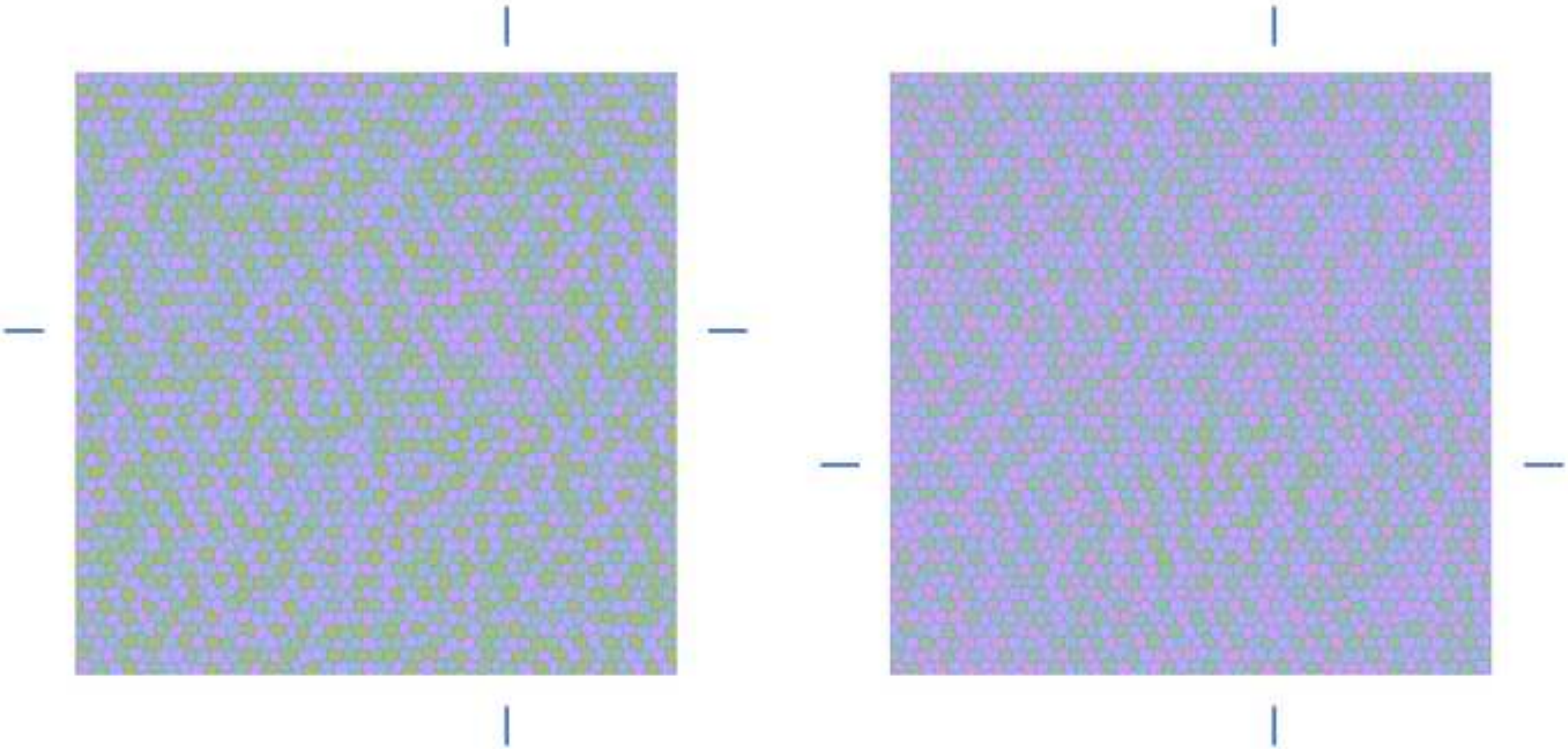
Slide07.tiff

Figure
Click here to download high resolution image



Slide08.tiff

Slide09.tiff



Figure

Click here to download high resolution image

Slide10.tiff