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Change detection is easier at texture border bars when they are parallel to the border: Evidence for V1 mechanisms of bottom – up salience

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Abstract. A vertical bar is salient among horizontal ones by orientation contrast, and, traditionally, bottom – up salience is viewed as caused only by feature contrast. Recently, it has been proposed that the primary visual cortex (V1) creates a bottom – up salience map in its outputs, which depends on direct inputs and on contextual inputs by intra-cortical interactions (Li Zhaoping, 2002 *Trends in Cognitive Sciences* **6** 9 – 16). Since the interactions include iso-feature (eg iso-orientation) suppression, responsible for salience by feature contrast, and collinear facilitation, the V1 proposal predicts that collinear grouping contributes to salience additionally. Accordingly, in orientation textures, texture bars are more salient near texture borders owing to orientation contrast, and are even more salient when they are additionally parallel to the border by collinear grouping. We show that colour changes in texture bars are more detectable when the bars are parallel to the texture border. Since changes are more detectable at salient locations, our finding supports V1 mechanisms for bottom – up salience.

1 Introduction

Perceptually, an item can be more conspicuous in some contexts than in others. For example, it is easier to find a red apple among bananas than among tomatoes; and the apple is said to be more salient in the former case than in the latter. This salience is regarded as a bottom – up factor since it is not determined by top – down task demands. Previous studies have shown that items with higher bottom – up salience usually have large feature contrasts against their surroundings (Nothdurft 1991, 1992, 2000; Treisman and Gelade 1980; Wolfe et al 1989). For example, a vertical bar is more salient among horizontal bars than among nearly vertical bars, since the orientation contrast is greater in the former case. Also, two neighbouring orientation textures are more easily segmented when there is a larger orientation contrast between them (Nothdurft 1992), since the texture border is more salient in attracting attention. Several theories and computational models have been developed to derive the bottom – up salience from feature contrasts (eg Itti and Koch 2000; Wolfe et al 1989). We call this type of model of salience *the feature-contrast model*.

While input feature values can be computed by V1 neurons, the feature-contrast model has left it unspecified which brain area computes the ultimate salience values in a salience map. Meanwhile, Li Zhaoping (2002; Zhaoping 2005)(1) proposed that neural outputs in V1 create a bottom – up salience map, and we call this *the V1 model* of salience. Using a computational model of V1 (Li 1998, 2000), she demonstrated that V1 computes salience in neural outputs through intra-cortical interactions to mediate contextual influences. Specifically, V1 neurons receive direct feature inputs, and also suppressive or facilitative inputs from neighbouring neurons. In the orientation-feature

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(1) Li Zhaoping's publications before late 2002 were published under the name "Zhaoping Li" (ie Li Z), and later under the name "Li Zhaoping" (ie Zhaoping L) and they are so listed in the references.

domain in particular, the response of a neuron to a bar is suppressed if this bar is surrounded by contextual bars; this is called the *general surround suppression*. This suppression is strongest when the contextual bars are parallel to the central bar (*iso-orientation suppression*—Knierim and van Essen 1992; Nothdurft et al 1999). Also, neural response is enhanced when contextual bars align with the central bar to form a smooth contour (*collinear facilitation*—Kapadia et al 1995; Polat et al 1998). Consequently, neurons responding to an oriented bar with a larger orientation contrast with their neighbours suffer less iso-orientation suppression and thus exhibit higher activities, and those responding to an oriented bar collinearly grouped with their neighbours are also more active because of collinear facilitation. According to the V1 model, the most active neurons report the most salient locations, when not only the feature contrast but also collinear grouping contributes to bottom–up salience.

In this study, we aim to test whether salience is determined only by feature contrast, or, additionally, by collinear grouping, as suggested by the V1 model. To simplify this question, we focus on input textures of uniformly oriented bars, as illustrated by two configurations in figure 1a. Each configuration has a *figure* texture sandwiched by the *ground* texture. When the figure texture bars are parallel or orthogonal to the border between the figure and the ground, we call this *a parallel configuration* or *an orthogonal configuration*, respectively. The ground texture bars are always orthogonal to those in the figure texture, making a 90° orientation contrast at the border. The feature-contrast model therefore predicts higher salience values for texture bars at the border than away from the border (figure 1b). Moreover, since the orientation contrast is 90° viewed from the figure or the ground, the predicted salience value of the border bars does not depend on whether they are in the figure or in the ground.

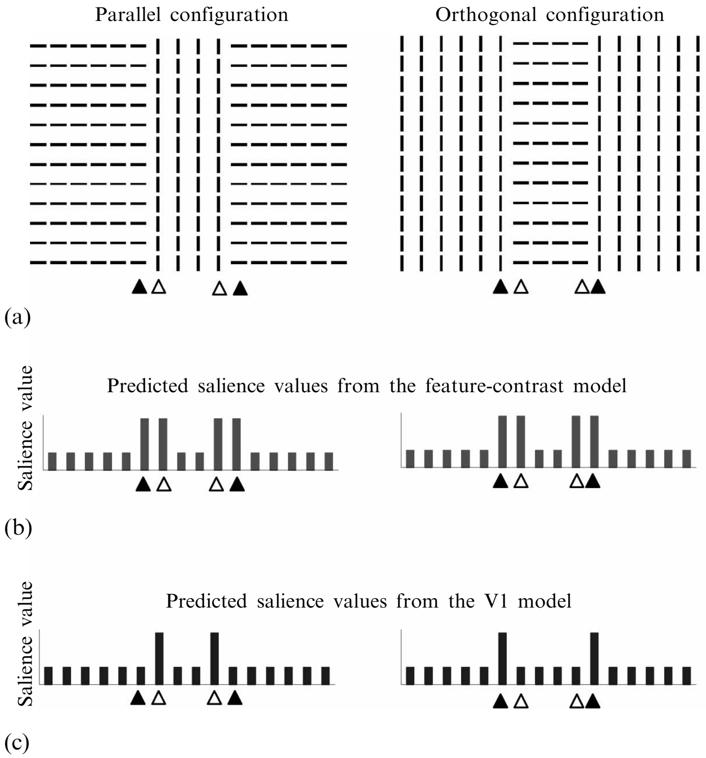


Figure 1. (a) Examples of two configurations used in this study, and the predicted salience values for these stimuli according to (b) the feature-contrast model and (c) the V1 model. Empty arrows are aligned with border bars in figure and filled arrows with border bars in ground.

In contrast, the V1 model (figure 1c) predicts higher salience values for texture border bars parallel to the border than ones orthogonal to the border (Zhaoping 2003). This is because the parallel border bars not only have fewer iso-orientation neighbours than the non-border bars, but also have more collinear neighbours than the orthogonal border bars, leading to even higher neural responses. The enhanced responses to the parallel border bars in turn suppress the responses to the orthogonal border bars in the neighbouring texture owing to general surround suppression. As a result, figure border bars are more salient in parallel configurations than in orthogonal configurations, the converse applying to ground border bars, as shown in figure 1c.

To test these predictions, a change-detection task (O'Regan et al 1999; Simons 1996) was used to probe salience values on both sides of the texture border. In our design, each texture bar has one of four colours. Randomly, two of the colours were assigned to the figure texture bars and the other two to the ground texture bars. Within each region, all bars in the same column or row have the same colour, and neighbouring columns or rows have different colours. One stimulus configuration was shown in two intervals with a blank in-between (the one-shot procedure). The task was to report whether there was a change of colour in the texture bars, regardless of whether the colour change occurred in the figure or ground texture. All the colour changes were such that a texture bar merely swapped colours with its differently coloured neighbour of the same texture region (see figure 2, modified from Mazza et al 2005). Therefore, it is difficult to perceive any global colour change between the two intervals, and the subjects had to direct attention locally to detect changes easily. Furthermore, whenever there was a change, it occurred in all figure bars or all ground bars, but never in both figure and ground. Therefore, change is most likely detected when attention is directed toward the border between the figure and the ground. Since changes at a more salient location are easier to detect (Cole et al 2003, 2004; Wright 2005), measuring change-detection rate enables us to probe the salience of the texture border. The feature-contrast model predicts that changes in the figure are equally detectable regardless of configurations, the same applying to changes in the ground. In contrast, the V1 model predicts that changes in the figure are more detectable in the parallel than orthogonal configurations, the converse applying to changes in the ground. In other words, if we denote some measure of abilities to detect changes in the figure and the ground in parallel and orthogonal configurations by $F_{\|}$ (figure change parallel), $F_{\perp}$ (figure change orthogonal), $G_{\|}$ (ground change parallel—note that the border bars in the background texture are orthogonal to the border in this case), and $G_{\perp}$ (ground change orthogonal), then the predictions of these two models are as follows:

From the feature-contrast model:

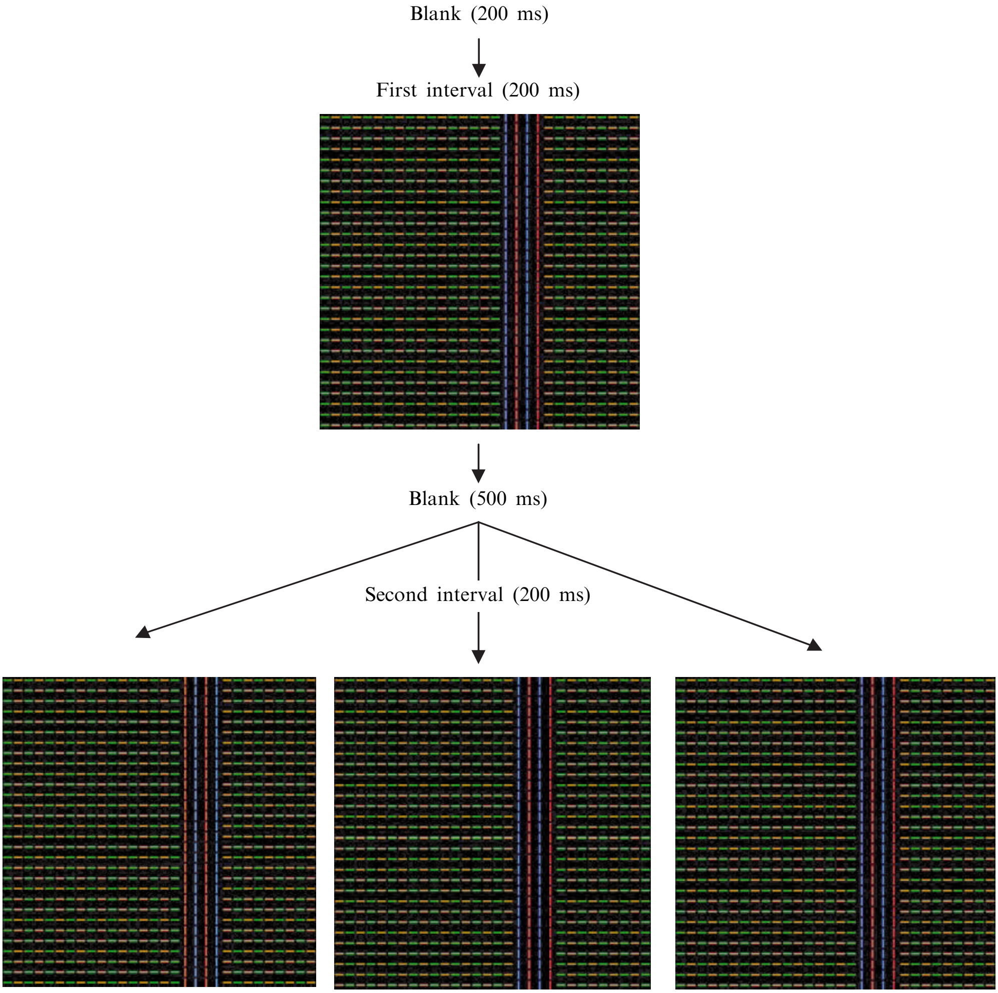
$$F_{\|} = F_{\perp}\,; \quad G_{\|} = G_{\perp}\,. \tag{1}$$

From the V1 model:

$$F_{\|} > F_{\perp}\,; \quad G_{\|} < G_{\perp}\,. \tag{2}$$

In this study, we measured change-detection rates in two experiments to test the above predictions. These two experiments differed mainly by the way texture colours were grouped in the stimuli. The stimuli for experiment 1 were like that illustrated in figure 2, in which texture colours were grouped in columns (or rows) parallel to the texture border. By contrast, the stimuli for experiment 2 were such that the colours were grouped in rows or columns orthogonal to the texture border (see figure 3). Experiment 2 was a control for experiment 1 to ensure that the change-detection rates to probe the texture border salience are not confounded by any perceptual or attentional factors arising from colour grouping.(2) Additionally, some other factors beyond bottom–up salience

(2) We thank Jeremy Wolfe for providing this alternative explanation.



(a) (b) (c)

Figure 2. The procedure and the examples of locus of change in the vertical-varied condition. (a) In figure-change trials, all red bars in the first interval change to blue in the second interval, and vice versa. (b) In ground-change trials, all green bars change to yellow and vice versa. (c) In no-change trials, the same configuration was shown in both intervals. The colour combinations were randomised in each trial.

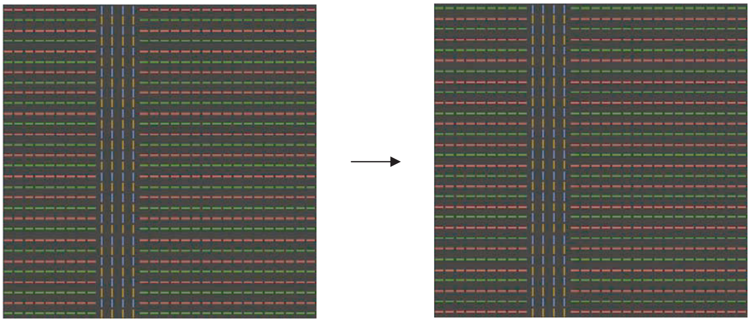


Figure 3. An example of the ground change in experiment 2. The colours of the texture bars are now grouped in rows or columns orthogonal to the texture border; otherwise they were the same as in experiment 1.

may also affect the task performance. First, detection rates in figure or ground may differ (Mazza et al 2005), perhaps favouring detection in figure or ground. This factor, nevertheless, does not affect predictions from either the feature-contrast or the V1 model of salience, since the predictions concern relative change-detection rates between configurations for figure only or ground only. Second, changes may be more detectable in vertical or horizontal bars, thereby creating a possible confound. To counter this, we included stimuli made by rotating those in figure 1a by 90°, such that figure (or ground) texture bars in any configuration could be either vertical or horizontal. The predictions are the same regardless of this rotation. Third, prior knowledge of the border location may enable the subjects to better direct their attention for change detection. We assessed this factor by measuring change-detection rates in two different situations: fixing or randomly varying border locations within an experimental session. In anticipation, we found that change-detection rates matched the predictions generated by the V1 model, rather than the feature-contrast model.

2 Experiment 1

In this experiment, four factors determined the stimulus: (i) configuration (parallel or orthogonal), (ii) locus of change (figure change, ground change, or no change), (iii) border orientation (vertical or horizontal), and (iv) figure location (fixed, or randomly varied). In each experimental session, factors (i) and (ii) randomly varied between trials. Each session is denoted by the parameters for factors (iii) and (iv): vertical-fixed, horizontal-fixed, vertical-varied, and horizontal-varied, and was shown to different participants.

2.1 *Method*

2.1.1 *Participants.* A total number of eighty participants took part, twenty for each session. They were paid volunteers from UCL psychology subject pool, and were unaware of the goal of the study before carrying out the experiment. All the participants had normal or corrected-to-normal vision, and did not have a colour deficit.

2.1.2 *Equipment and stimuli.* Stimuli were presented on a gamma-corrected 21 inch Sony GDM-F520 monitor, driven by a personal computer with a visual stimulus generator (ViSaGe, Cambridge Research System). The screen refresh rate was 170 Hz, the resolution 800×600 pixels, and the viewing distance 67.6 cm. The texture bars were vertical or horizontal $0.59 \text{ deg} \times 0.11 \text{ deg}$ rectangles presented on a 0 cd m^{-2} background, each centred on a grid point in a 30×30 uniform grid with unit grid distance of 0.73 deg (see figure 2). Each texture bar was coloured with one of the four equal-luminance (18.07 cd m^{-2}) colour choices: green (CIE 1931 coordinates $x = 0.314$, $y = 0.488$), red ($x = 0.430$, $y = 0.317$), blue ($x = 0.235$, $y = 0.218$), and yellow ($x = 0.437$, $y = 0.472$). In each stimulus, randomly two colours were assigned to the figure bars and the other two to the ground bars. Taking the case of vertical border for example, see figure 2, each column of texture has the same colour, and any two neighbouring columns have two different colours. Analogously, in the case of the horizontal border, the iso-coloured columns are now iso-coloured rows. The figure has four columns or rows of texture bars.

2.1.3 *Design.* In each session, two factors, configuration and locus of change, were interleaved. In the stimulus-change trials, colours were swapped between the neighbouring columns or rows of bars within the same texture region (figure 2), whether this region was the figure (figure change, figure 2a) or the ground (ground change, figure 2b). In the no-change trial, the same stimuli were shown twice (figure 2c). Each participant completed one of the four sessions: vertical-fixed, horizontal-fixed, vertical-varied, and horizontal-varied. When figure location was fixed, it was at the centre of the screen in every trial in that session. When figure location was varied, its location in each trial was randomly chosen as one of five possibilities closest to the centre location, and was fixed within each trial.

2.1.4 *Procedure.* One example of figure change and another of ground change were shown to subjects during instructions before data taking. Their orders of presentation were counterbalanced between participants. The participants were not given any strategy for detecting changes; nevertheless, most of them confirmed after the experiment that they realised soon after the session started that paying attention to the border between textures helped. The procedure of each trial was as follows (figure 2): each trial began with a 200 ms blank display, a first interval of 200 ms, a blank of 500 ms, followed by the second interval for 200 ms. The display then stayed blank until subject's response, followed by the next trial after 800 ms. The participants pressed the "yes" button when they detected a change, and otherwise the "no" button. Each session consisted of 180 trials, 30 for each combination of locus of change and configuration condition, in a randomly interleaved sequence. Each session started with 12 practice trials, had a break every 60 trials, and typically took about 15 min.

2.2 *Results*

The percentages of "yes" responses are shown in figure 4. The percentages of "no" responses in no-change trials were 89.50%, 85.92%, 82.83%, and 81.08% for vertical-fixed, horizontal-fixed, vertical-varied, and horizontal-varied conditions, respectively. Regardless of border orientations and figure locations, the results show that figure changes were more detectable (ie with higher "yes" rate) in the parallel than orthogonal configurations, and the other way round for the ground change. From the "yes" rates for figure or ground changes, we calculate sensitivity $d' = z_\text{h}$ (hit rate = yes rate for change trials) $- z_\text{f}$ (false alarm rate = yes rate for no-change trials), according to the signal detection theory (see Macmillan and Creelman 2004). Note that the same false

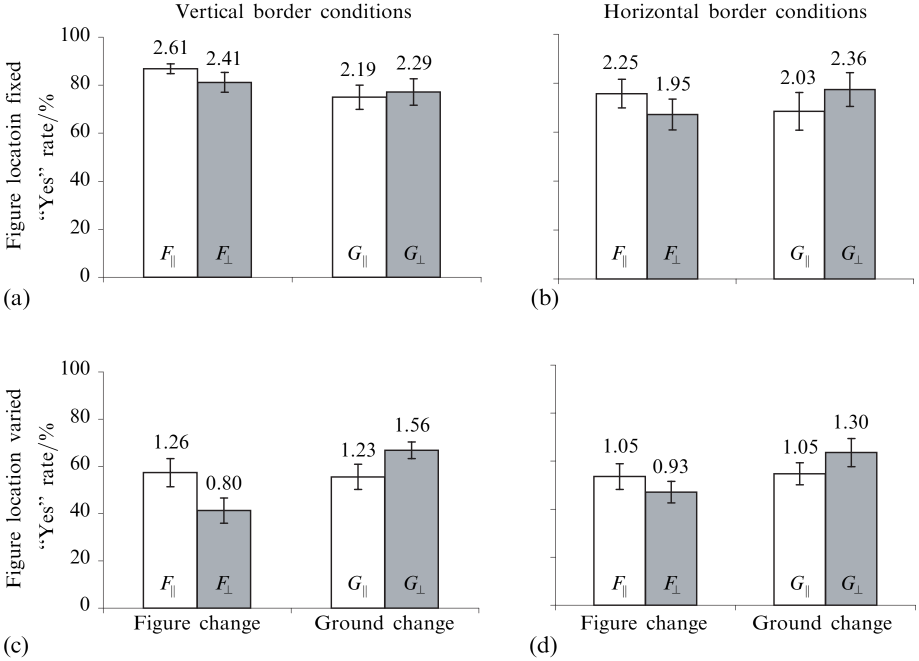


Figure 4. The percentage of "yes" responses for the condition of (a) vertical-fixed, (b) horizontal-fixed, (c) vertical-varied, and (d) horizontal-varied. The error bar is the standard error. The mean sensitivity (the d' score) is shown on top of the corresponding bars.

alarm rate applies to all conditions within a session, regardless of whether it is a figure or ground change, or whether it is a change in parallel or orthogonal configurations.

To relate our data to our purpose of testing the two theoretical models, we define a parallel border asymmetry index:

$$\text{Index} = (\text{F}_{\parallel} - \text{F}_{\perp}) + (\text{G}_{\perp} - \text{G}_{\parallel})\,. \tag{3}$$

According to our predictions in equations (1) and (2), this index should be zero for the feature-contrast model and positive for the V1 model. We calculated this index by using d' values for each change condition, and found that this index was significantly larger than zero in all our conditions: 0.31, 0.67, 0.81, and 0.45 for conditions of vertical-fixed ($t_{19} = 2.42$), horizontal-fixed ($t_{19} = 3.29$), vertical-varied ($t_{19} = 5.11$), and horizontal-varied ($t_{19} = 2.66$) conditions, respectively, $p\text{s} < 0.05$, thus supporting the V1 model.

To reveal more details, the d' scores were submitted to a four-way analysis of variance (ANOVA) with between-subject factors: border orientation (vertical or horizontal) and figure location (fixed or varied), and within-subjects factors: configuration (parallel or orthogonal) and locus of change (figure or ground change). The significant results from the ANOVA showed:

(i) In agreement with our index conclusion above, the interaction between configuration and locus of change was significant ($F_{1,76} = 36.37$, $\text{MSE} = 0.17$, $p < 0.001$). The simple main effect of the interaction showed that figure changes were better detectable in parallel than in orthogonal configurations ($F_{1,152} = 25.14$, $\text{MSE} = 0.31$, $p < 0.001$), while ground changes were better detectable in orthogonal than in parallel configurations ($F_{1,152} = 22.45$, $\text{MSE} = 0.31$, $p < 0.001$).

(ii) Also, in the parallel configuration, figure changes have higher d' than ground changes ($F_{1,152} = 4.38$, $\text{MSE} = 0.41$, $p < 0.05$); while in the orthogonal configuration, ground changes are better detectable than figure changes ($F_{1,152} = 11.72$, $\text{MSE} = 0.41$, $p < 0.001$). This interaction is consistent with the V1 model but not the feature-contrast model (see figure 1).

(iii) A significant main effect of figure location ($F_{1,76} = 28.75$, $\text{MSE} = 3.25$, $p < 0.001$) was found, namely d' was higher for the fixed than the varied condition. Therefore, unpredictable figure locations increased task difficulty.

(iv) There was an interaction between figure location and locus of change ($F_{1,76} = 4.03$, $\text{MSE} = 0.65$, $p < 0.05$), and the simple main effect showed that d' were higher for fixed than varied conditions for both figure changes ($F_{1,152} = 32.66$, $\text{MSE} = 1.95$, $p < 0.001$) and ground changes ($F_{1,152} = 16.63$, $\text{MSE} = 1.95$, $p < 0.001$). This difference in d' is smaller for the changes in the ground, which is because ground changes were better detectable than figure changes in the varied condition ($F_{1,76} = 3.80$, $\text{MSE} = 0.65$, $p = 0.055$). Both findings (iii) and (iv) are not relevant to the hypothesis testing, since they do not distinguish between the V1 and the feature-contrast model, and reflect factors beyond bottom – up salience.

In summary, our findings support the V1 model in that the parallel border asymmetry index was significantly larger than zero in all four conditions, and as confirmed by the significant interaction between configuration and locus of change.

3 Experiment 2

In experiment 1, texture colours were grouped in rows or columns parallel to the border between the figure and the ground (figure 2). This may cause the participants to pay more attention to the bars that are parallel to the direction of colour grouping and thus bias the change-detection rate in favour of the prediction of the V1 model. To avoid this confound, we grouped colours in the direction orthogonal to the border (see figure 3) so that the attentional set, if it existed, should be orthogonal to the texture border. If the parallel border asymmetry index is still higher than zero, we can then conclude that the changes in texture regions with bars parallel to the border were indeed better detectable in a bottom–up manner. The vertical-varied condition was chosen, for it can elicit the most reliable effect in experiment.

3.1 *Method*

3.1.1 *Participants.* Eighteen volunteers from the China Medical University in Taiwan joined this experiment for extra course credits. They had normal or corrected-to-normal vision and did not have a colour deficit. They had no previous experience of the change-detection tasks, and were not aware of the goal of the study.

3.1.2 *Equipment and stimuli.* The experiment was carried out in a dimly lit room. Stimuli were shown on a 21 inch ViewSonic Professional P227f monitor, driven by a dual-core PC. The program was written with Psychophysics Toolbox extension in Matlab (Brainard 1997; Pelli 1997). Four equal-luminance (19.85 cd m^{-2}) colours were used (measured by CS100A): green (CIE 1931 coordinates $x = 0.306$, $y = 0.551$), red ($x = 0.515$, $y = 0.329$), blue ($x = 0.199$, $y = 0.175$), and yellow ($x = 0.457$, $y = 0.456$). Other details were the same as in experiment 1.

3.2 *Results*

The average percentage of "no" was 87.50%, and the percentages of "yes" were 69.63%, 71.67%, 60.93%, and 74.81% for the $F_{\parallel}$, $G_{\parallel}$, $F_{\perp}$, and $G_{\perp}$ conditions, respectively. The parallel border asymmetry index was 0.34 for d' scores, and was significantly higher than zero ($t_{17} = 2.68$, $p < 0.05$). Again, we found that the change detection was better recognised when it occurred in a texture region with bars parallel to the texture border, thus supporting the V1 model.

4 General discussion

In this study, we found changes in a texture to be more detectable when the texture bars are parallel to the border. This was regardless of the orientation of the texture bars or the border, and whether the change was in the figure or ground texture region, and regardless of the predictability of the border location, and of the grouping direction of the colours of the bars. Since changes are more detectable at more salient locations, our data suggest higher bottom–up salience values for border bars parallel to the texture border.

Related to our work is the finding by Nothdurft on a texture segmentation task, reporting the orientation of the long axis of a rectangular figure texture made of two rows or columns of bars (Northdurft 1992). This task is equivalent to reporting the orientation of the longer border of this rectangular-figure texture. Given an orientation contrast between the figure texture bars and the ground texture bars, the performance was better when the figure texture bars were collinear or parallel to the longer border of the figure. Nothdurft suggested that this finding reflects the additional contribution to salience by collinear alignment of bars, though this contribution is weaker than that from the feature contrast. Another related finding is by Wolfson and Landy (1995) who measured the performance in discriminating the curvature of a border between two textures of bars. They found that the performance was slightly better when the bars in one texture region were parallel to the border, and argued that such a configuration made the texture border stronger or more salient. We note that in both studies the tasks to discriminate border orientation or curvature did not distinguish well whether the border salience was due to one texture region or the other, or both. In particular, given a large orientation contrast as the texture bars in one region become more parallel to the border and those in the other region become more orthogonal to the border, this makes it difficult to measure the degree to which collinear alignment contributes to salience. For the goal of our study, we need to distinguish contributions from the parallel and the orthogonal border bars, and ignore the contribution to salience by the orientation-feature contrast which does not distinguish between the V1 and feature-contrast models. In particular, our task of change detection, when change occurs in one texture region only, specifically enabled us to separately probe salience contributions from different border bars. Furthermore, our task is a *detection* task in nature, while the tasks used in previous studies have been *discrimination* tasks. It has been argued (Nothdurft 2002; Sagi and Julesz 1986) that detection tasks are executed faster than, or prior to, discrimination tasks. Detection tasks are thus more suitable to probe salience which functions more as *detection* of conspicuous but not yet recognised (or discriminated) items to guide attention for subsequent discrimination. Therefore, our finding provides additional and more direct evidence for the existence of collinear grouping mechanisms for bottom – up salience.

To model or account for collinear or alignment effects, previous investigators (eg Wolfson and Landy 1995) introduced additional filtering or channel mechanisms called second-order filters, subsequent to the first-order filters responsible for the mechanisms by feature contrast. Our V1 model does not conflict with these previous models, but can be seen as a neural basis behind earlier models which are phenomenological in nature. While we did not test this in this study, the neural basis of V1 suggests that mechanisms for collinear and feature-contrast effects are at the same stage of processing. Hence, our study adds to many previous studies of the neural basis of salience, including physiological studies (Kapadia et al 1995; Knierim and van Essen 1992; Nothdurft et al 1999), fMRI studies (eg Beck and Kastner 2005), and behavioural studies (Jingling and Zhaoping 2005; Koene and Zhaoping 2007; Zhaoping 2008; Zhaoping and May 2007).

In conclusion, by using the change-detection tasks the relative salience of two textures around the texture border can be separately accessed. We found that border bars parallel to the texture border are more salient. Our data suggest that the bottom – up salience is not determined only by feature contrast, but consistent with the V1 model of salience, concerns both feature contrasts and collinear grouping.

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